Simultaneous Electromagnetic Measurement Using a Parallel Modulated Probe Array

Qiang Chen, *Member, IEEE*, Kunio Sawaya, *Senior Member, IEEE*, Tomohiro Habu, and Ryoichi Hasumi

***Abstract*—A simultaneous measurement method using a parallel modulated probe array is proposed to measure the electromagnetic field radiated by antennas at different locations simultaneously. Each modulated probe is excited by a local signal with different frequency, so that the received intermediate frequency (IF) signal contains different frequency components which indicate the relative magnitude of the radio-frequency signal at positions of the probes, and all the IF components are measured simultaneously by a broadband microwave receiver. The effect of the local signal on the received IF signal and interaction effect between the probe array and the measured antenna are investigated. The accuracy of the method is shown by measuring the antenna radiation pattern. A 3-D antenna radiation measurement system based on the present method is also developed. The performance of the system is demonstrated by measuring the radiation efficiency of antennas.**

***Index Terms*—Electromagnetic (EM) field, measurement, modulation, probe, probe array.**

I. Introduction

The RADIATION pattern of antennas is usually measured by rotating the antenna under test (AUT) on a turntable. This conventional measurement usually takes several tens of seconds to several minutes depending on the speed of the rotation and the number of sampling points. Measurement of the radiation efficiency of antennas based on the pattern integration method may take more than 10 min if the mechanical turntable and spherical scanner are used [1]. However, in practical antenna design, it is strongly required to reduce the measurement time to measure the 3-D radiation pattern of antennas as fast as possible.

In the field of electromagnetic compatibility (EMC) research, it is required to measure the electromagnetic (EM) radiation that is instant and irregular, such as the leaked EM radiation from the electric devices [2]. The radiated field should be measured simultaneously in several locations around electric devices in order to estimate the source locations. Therefore, a method that is capable of measuring the EM radiation simultaneously at several locations is necessary.

A measurement method using the modulated scattering technique (MST) has been proposed to measure the EM field rapidly [3]–[9]. The MST measurement employs an array of modulated scattering elements (MSEs) that are successively modulated by a low-frequency modulation signal. The EM field radiated by the AUT is received and modulated by the MSE. The modulated field scattered by the MSE is either received by the AUT or by an auxiliary antenna to obtain the distribution of the incident electric field on each MSE. Since only a low-frequency multiplexer and a power dividing network are employed to connect all the MSEs, instead of the expensive microwave switching networks, the MST measurement is a simple and economical method for measuring the EM field at a large number of observation points rapidly. The MST measurement is actually a rapid measurement but not a simultaneous measurement, because the low-frequency modulation signal is successively scanned over the MSEs to distinguish the observation points.

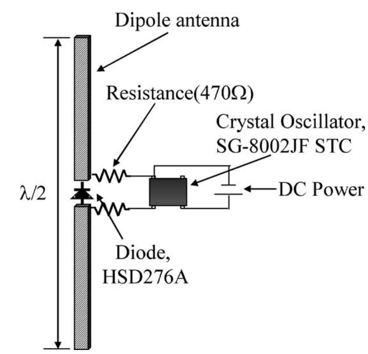

Fig. 1. Structure of the MSE.

In this research, a simultaneous measurement method using the parallel modulated probe array is proposed. Each modulated probe element is modulated by a low-frequency modulation signal with different frequency. The modulated signal is combined, and a broadband microwave receiver is received. This proposed method is applied to the measurement of the radiation pattern and the radiation efficiency of the measured antennas to show the performance of the present method.

II. Simultaneous EM Measurement Method

The measurement method using the parallel MST is described by using the following experimental setup [10].

A dipole scatterer with a Schottky diode mounted at the center of the dipole, as shown in Fig. 1, is used as the MSE in the measurement system. An 18-element MSE array is mounted on a ring with equal angles, and the AUT is located at the center of the circular ring, as shown in Fig. 2. The MSE has a half-wavelength at frequency of measurement $(f_{\rm RF})$. A local signal low frequency $(f_{\rm LO})$ is generated by a crystal powered by a battery. Two resistors with large resistance are inserted in the wires between the diode and the crystal to make the wires have high impedance in order to reduce the radiation by the wires. Incident EM field from the AUT with frequency $f_{\rm RF}$ on the

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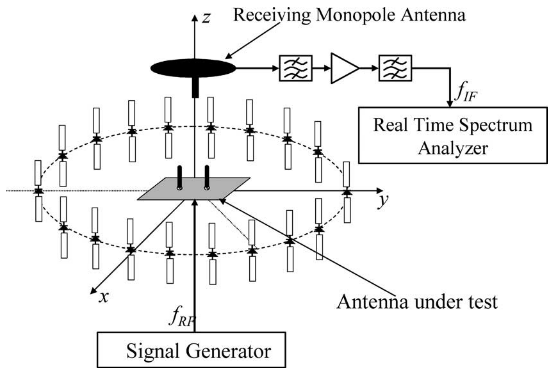


Fig. 2. Measurement system using the MSE array.

MSE array is modulated by the local signal on the diode, and the modulated signal with frequency f_{IF} is scattered by the MSE array. The modulated intermediate frequency (IF) signal with frequency $f_{\mathrm{RF}} + f_{\mathrm{LO}}$ is received by one receiving antenna located at the axis of the ring and detected by a microwave receiver. Because each MSE is excited by a local signal with different frequency, the received IF signal contains different frequency components that indicates the relative magnitude of the radio-frequency (RF) signal at positions of the MSE, and all of the IF frequency components are measured simultaneously by the wideband microwave receiver. Since it is assumed here that only the vertical polarization is measured, the MSE dipole is vertically located and a vertical monopole antenna is used as the receiving antenna for receiving IF signal.

A real-time spectrum analyzer (Tektronix RSA 3303A) is used as the wideband microwave receiver. The programmable crystal oscillators (Epson SG-8002JF) are turned to generate a different frequency for each MSE. The circular ring for supporting the MSE array is made of polystyrene foam with a diameter of 1.2 m. The measurement system is located inside an anechoic chamber. Although only the vertical polarization is measured by this measurement system, the horizontal polarization can be measured by using the MSEs of the horizontal dipoles and an electrically small loop antenna instead of the monopole as the receiving antenna.

Before the measurement, the effect of the directivity of the receiving antenna toward each MSE and the dispersion of the MSE characteristics is removed by a calibration measurement where a vertical dipole antenna with a homogeneous radiation pattern in horizontal plane is measured as a calibration source.

III. Results of Measurement

In this section, the performance of the MSE is investigated. The relation between the input RF power and the received IF power of one MSE is measured and shown in Fig. 3, where a signal generator (NF function synthesizer WF-1966) is used to generate the local signal instead of the crystals to control the power level of the local signal. The AUT is a half-wavelength dipole antenna. Effect of the local signal level on the received IF signal is also investigated. Fig. 4 shows the power of the received IF signal versus the power of the local signal. It is found in Fig. 3 that the received IF power at 1-dB compression occurs at around −65 dBm. It is also found in Figs. 3 and 4 that the receiving sensitivity can be improved by increasing the power of the local signal. Therefore, a larger power of the local signal may be a better choice in practical measurement if the RF–IF linearity is confirmed.

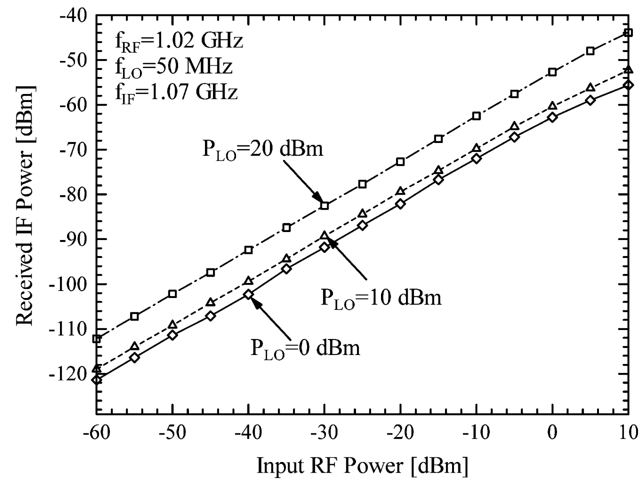


Fig. 3. Linearity of the measurement system.

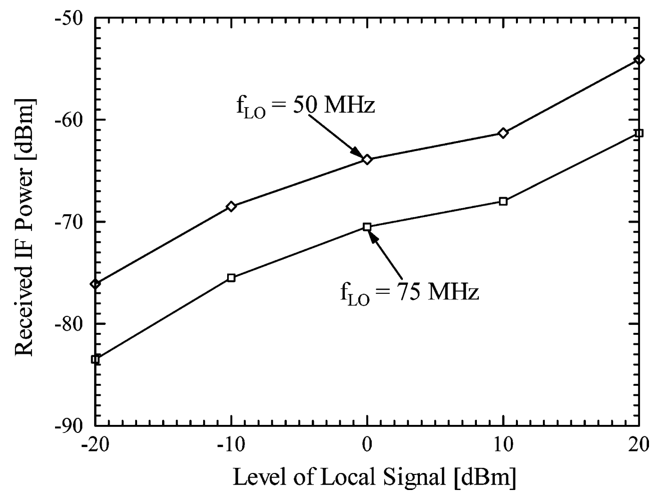


Fig. 4. Effect of the power level of the local signal.

The effectiveness of the simultaneous EM measurement method is verified by measuring the radiation pattern of a two-element quarter-wavelength monopole array. The array spacing is a quarter-wavelength and phase difference is about 90° so that the array antenna has an end-fire radiation pattern. Fig. 5 shows the spectrum of the received IF signal observed by the real-time spectrum analyzer. The peaks of the spectrum correspond to the RF signal level excited on different MSEs. Fig. 6 shows the radiation pattern measured by the MSE array compared with that of the conventional method where the measured antenna is rotated mechanically on a turntable and the far field of the measured antenna is directly received by a fixed receiving antenna. A good agreement between the two methods is obtained. In Fig. 6, 36 measurement points are plotted, although there are only 18 MSE elements. It is because the simultaneous measurement was made two times and a 10° rotation of the measured antenna was made after one measurement.

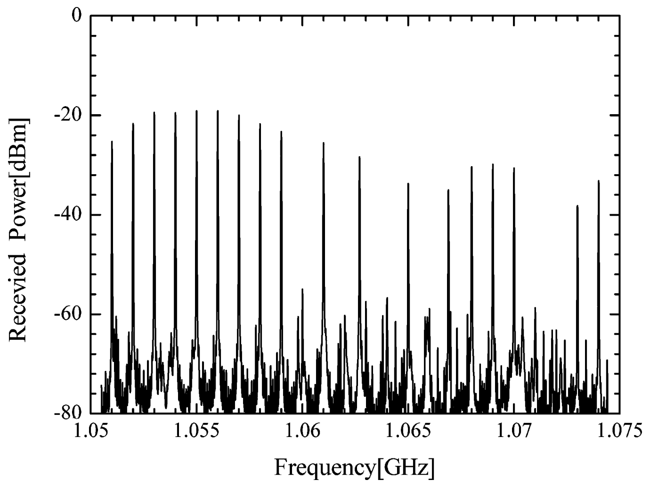


Fig. 5. Spectrum of the received IF signal.

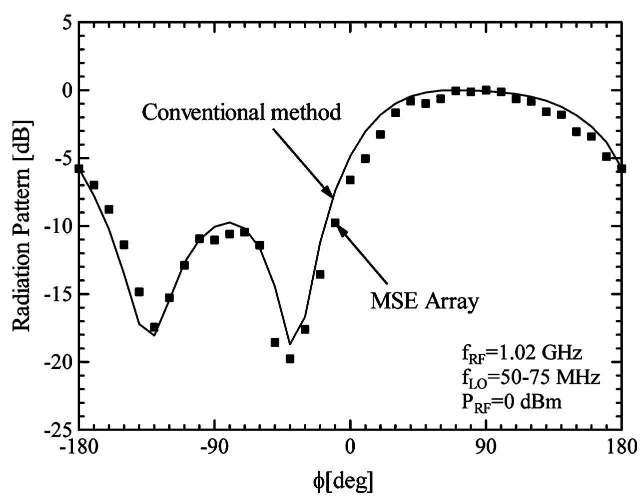


Fig. 6. Radiation pattern of the vertical polarization two-element quarter-wavelength monopole array.

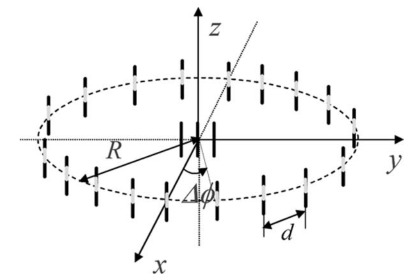


Fig. 7. Three-element Yagi–Uda antenna is measured by the MSE array on a full circular ring.

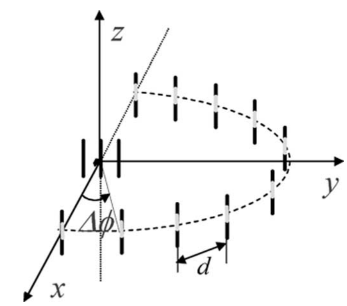


Fig. 8. Three-element Yagi–Uda antenna is measured by the MSE array on a half circular ring.

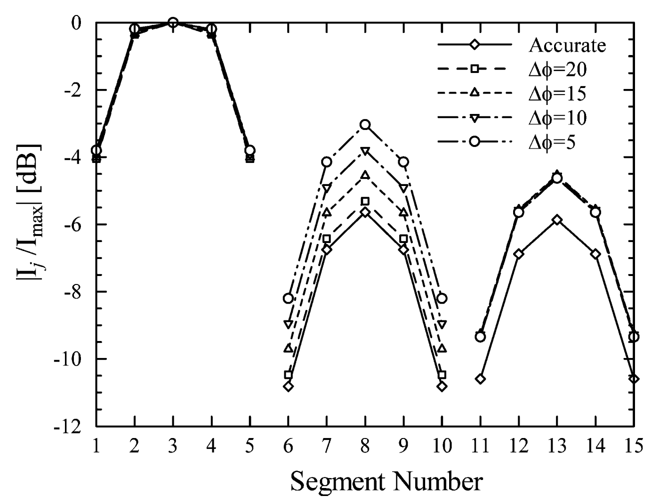


Fig. 9. Current distribution on three-element Yagi–Uda antenna surrounded by the MSE array on a full circular ring.

IV. Effect of AUT–MSE Array Interaction

Although the present method is applied to the far-field measurement, the interaction between the measured antennas and the MSE array has to be considered due to the limited radius of the ring where the probe array is mounted, because the interaction could affect the original current distribution of the measured antennas and decrease the accuracy of the measurement. In order to investigate the interaction effect, the measurement is numerically analyzed by using the moment method. In the analysis, a circular full-ring model (Fig. 7) and a half-ring model (Fig. 8) are assumed. Also, the array spacing that is denoted by the angle of two neighbor array elements is changed from 5° to 20°, which corresponds to the number of array element from 72 to 18 for a full-ring model and 36 to 9 for a half-ring model, respectively. A three-element Yagi–Uda dipole array antenna is used as the AUT. The normalized current distribution of the three-element Yagi–Uda dipole array antenna for different ring models and different MSE separation angles ($\Delta\Phi$) are calculated and shown in Figs. 9 and 10. In the figures, the "accurate" curve is obtained when the MSE array is not included in the analysis model. The current on the fed dipole is from segment number 1 to 5, and the current on the reflector and conductor are from 6 to 10 and 11 to 15, respectively. It is found that even if the radius of the ring is as large as 0.6 m, about two wavelengths at an operating frequency of 1.02 GHz, the effect of the interaction on the current distribution of the measured antenna is still significant. For example, the full-ring geometry and a separation angle of 10° could degrade the original current distribution up to 2 dB. A large separation angle (small number of array elements) can decrease the interaction effect. Furthermore, the half-ring geometry is better than the full-ring geometry from the viewpoint of the interaction.

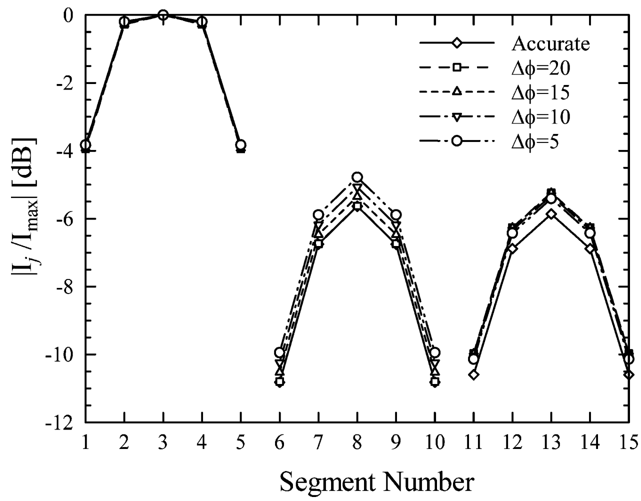


Fig. 10. Current distribution on three-element Yagi–Uda antenna surrounded by the MSE array on a half circular ring.

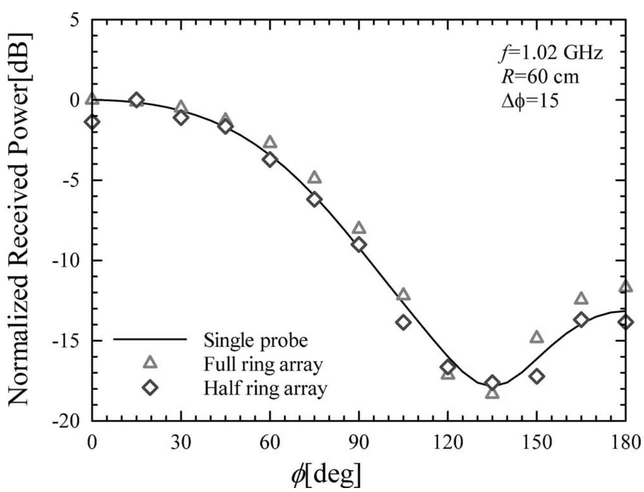


Fig. 11. Numerical simulation of the radiation pattern of three-element Yagi–Uda array measured by single probe, MSE array on full circular ring, and MSE array on a half circular ring.

Fig. 11 shows the numerical results of the radiation pattern of the three-element Yagi–Uda array measured by a single probe, the MSE array on full circular ring, and the MSE array on half circular ring, respectively. It is found that the pattern of the half circular ring agrees better with the pattern measured by single probe than does the pattern of the full circular ring, except the points at 0° and 180°, because the probes at the two ends of the half ring have different array element pattern from the other probes. However, this error can be compensated by calibrating the array element pattern of the probe elements in the practical measurement system.

V. 3-D Antenna Radiation Measurement System

In order to measure the 3-D radiation pattern and radiation efficiency of the antennas, a measurement system using the parallel modulated probe array was developed. Fig. 12 shows the configuration of the measurement system. The probe array that is composed of 16 modulated probe elements is mounted on a semicircular arch with equal angular spacing from 0° to 168.75° in elevation angle. The arch and the prop for mounting the AUT are made in a low-dielectric constant material. The probe array, together with an azimuth turntable, makes it possible for the measurement system to measure the radiation field on a spherical surface including the AUT located on the turntable. The radius of the sphere is 1.03 m. The modulated probe is composed of a cross-dipole antenna and a shielding box that contains modulation circuits. Each probe has a crystal generating a local signal with different frequency ranging from 20 to 40 MHz for modulation with the received RF signal. The modulated signals with different frequency are combined by RF combiners and inputted to a wideband spectrum analyzer. The polarization of the modulated probe array is switched electrically. The manufactured measurement system is shown in Fig. 13. The cross-dipole antenna that has a resonant frequency of 1 GHz is shown in Fig. 14. The polarization isolation of the cross-dipole antenna is more than 30 dB. The modulation circuit box of each modulated probe includes electric circuits for modulation and amplification. The gain of the modulated probe is about 10 dB at 1 GHz.

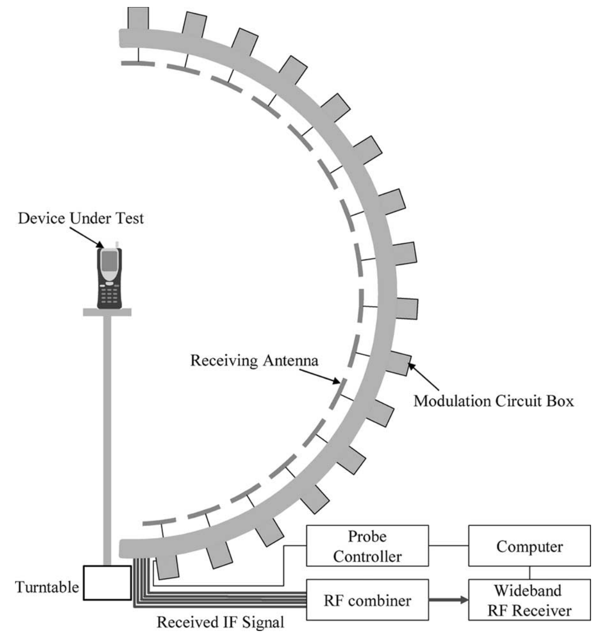


Fig. 12. Configuration of the 3-D EM measurement system using a modulated probe array.

Theoretically speaking, the frequency of the measured signal is not limited by the present method itself. However, the developed measurement system based on this method has a limited frequency range that is mainly determined by the frequency range of the probe antennas and the modulation circuits. The signal-to-noise (S/N) ratio would degrade if the signal beyond the frequency range of the system is measured. The lowest frequency is also determined by the distance between the probe and the AUT because the method is effective in the far-field measurement rather than in the near-field measurement. The present measurement system has a frequency range of 800 MHz to 1.2 GHz.

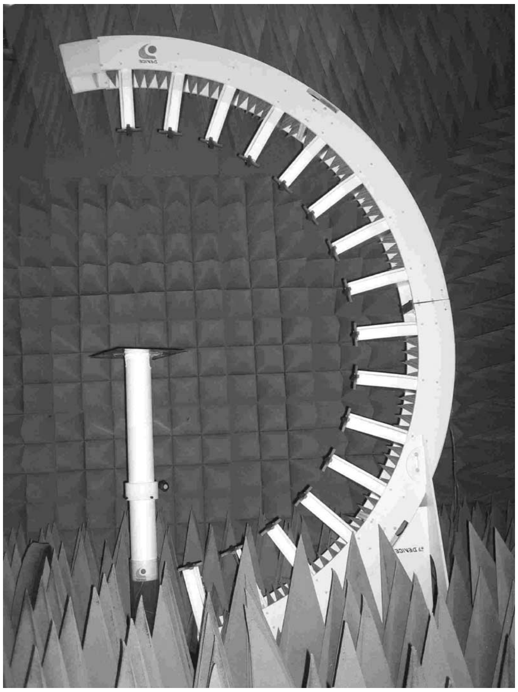


Fig. 13. Photo of the 3-D EM measurement system.

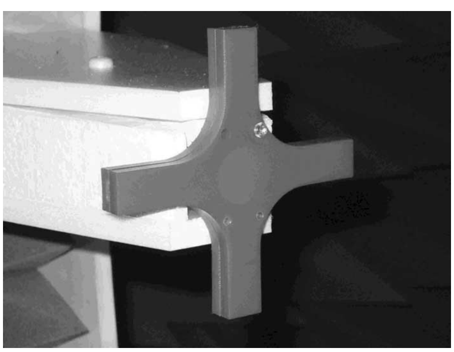


Fig. 14. Photo of the modulated probe element.

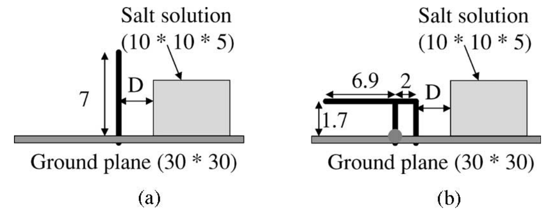


Fig. 15. Geometry of the measured antennas (in centimeters). (a) Monopole antenna. (b) Inverted F antenna.

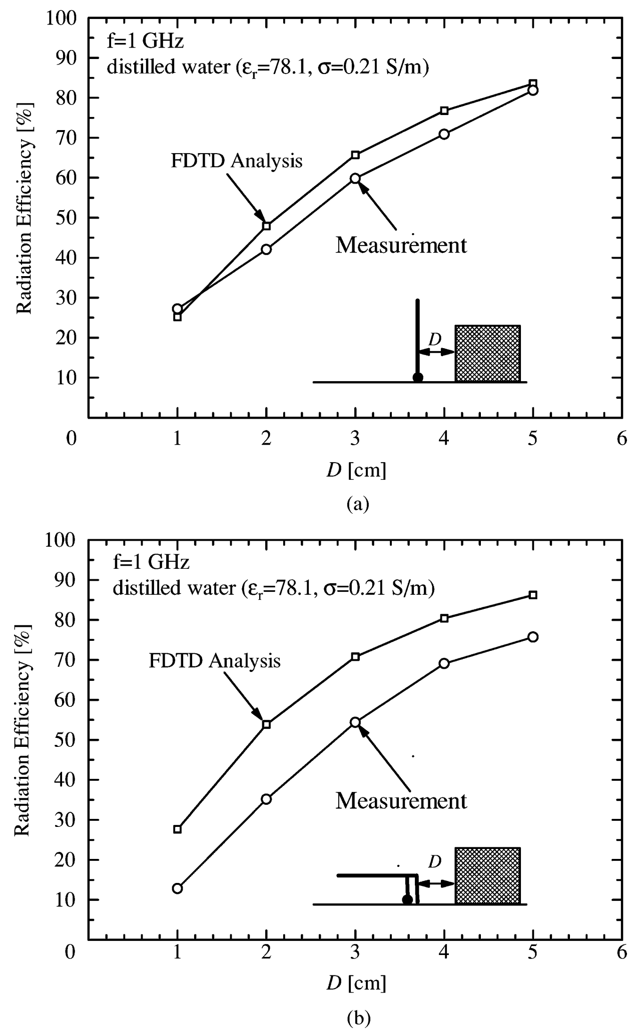
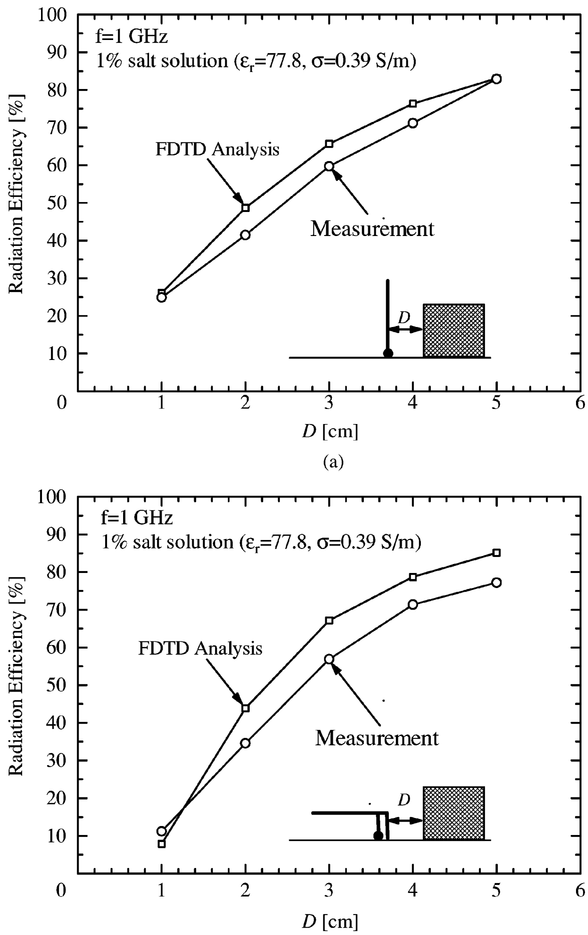


Fig. 16. Measured and calculated radiation efficiency of antennas near a container filled with distilled water. (a) Monopole antenna. (b) Inverted F antenna.

Because the position of the probe array is fixed in the measurement system, the spatial resolution is dependent on the array spacing of the probe array. A closer array spacing may result in a higher resolution, but it can decrease the receiving S/N ratio because the antenna gain of the probe antennas decreases due to a mutual coupling between array elements if the array spacing is much less than a half-wavelength. Therefore, when the distance between the probe and the AUT is fixed, the higher the operating frequency, the higher the spatial resolution can be realized. In the developed measurement system, the array spacing of about 20 cm that is larger than a half-wavelength at 800 MHz results in a spatial resolution of 11.25°.

Dynamic range is one of the most important parameters to evaluate the performance of the measurement method. Since the frequency modulation is performed simultaneously at all probes with different local frequencies, the harmonic components of the local signal appearing at the IF frequency can increase the noise level and degrade the received S/N ratio. Furthermore, since the microwave receiver should receive the IF signal at a wideband frequency domain, the thermal noise of the receiver also decreases the S/N ratio of the receiving signal. Therefore, the dynamic range of the present method is relatively low compared with the conventional MST measurement where only one local frequency is necessary. The narrowest dynamic range of the developed measurement system is about 30 dB at 800 MHz.

The radiation efficiency of two antennas is measured. One is a wire monopole antenna and the other is a wire inverted F antenna. The geometry of these antennas is shown in Fig. 15. The measured antenna is located in the vicinity of a rectangular



(b)

Fig. 17. Measured and calculated radiation efficiency of antennas near a container filled with a salt solution. (a) Monopole antenna. (b) Inverted F antenna.

container filled with a salt solution. The power loss in the salt solution is considered to be a part of the antenna loss. The radiation efficiency is defined to be the ratio of the radiated power to the incident power to the antenna. The radiation efficiency is changed by changing the parameter D, the distance between the salt solution container and the antenna. The radiation efficiency versus D is measured and compared with the numerical results by using the finite-difference time-domain (FDTD) method. In the numerical analysis, the dielectric parameters of the salt solution are obtained from [11]. Since it is difficult to include conductor loss in the FDTD method exactly, antennas are assumed to be made of a perfect conductor in the numerical analysis.

The comparison of the measurement and the numerical analysis is shown in Figs. 16 and 17, where the container is filled with distilled water and salt solution, respectively. The measured radiation efficiency is almost always larger than the calculated one by about 10% in the case of the inversed F antenna except for one point (salt solution and $D = 1$ cm). It is because the conductor loss is not included in the FDTD analysis, although it is relatively large for electrically small antennas like the inversed F antenna. An acceptable agreement between the measurement and the numerical analysis has been obtained in the case of the monopole antenna.

It is noted that it takes only about 16 s to measure one value of the radiation efficiency of antennas by using the present measurement system.

VI. Summary

A simultaneous measurement method using the parallel modulation technique has been proposed. The modulated probe element and the measurement system have been developed for performance investigation. The effect of the local signal on the received IF signal and interaction effect between the probe array and the measured antenna have been investigated. It has been found that a large local signal can increase the power of the received IF signal, and the half-ring array geometry is better than the full-ring geometry in reducing the interaction effect. The accuracy and the effectiveness of the present method have been demonstrated by the agreement between the present method and the conventional method with a mechanical turntable in the measurement of a 2-D antenna radiation pattern. A 3-D antenna radiation measurement system has also been developed. The radiation efficiency of antennas has been measured by the system, and the measurement results have been compared with the numerical results. It has been demonstrated that radiation efficiency of antennas can be measured rapidly with satisfactory accuracy.

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