

## A Simultaneous Measurement of Absolute Gain of Antennas in the Solution and its Dielectric Properties

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### 1. Introduction

A microwave computed tomography, which is abbreviated to microwave CT, has been researched for about two decades to develop a non-invasive biological imaging system using the electromagnetic wave [1][2]. In the microwave frequency band, it is clarified that the complex permittivity of biological tissue depends on the temperature [1]. The distribution of the complex permittivity inside the living body can be obtained if irradiating an electromagnetic pulse to the living body, measuring its penetration quantity and applying the CT technique. As a result, we can obtain the distribution of temperature change inside the living body through non-invasive imaging. In the measurement, biological objects are immersed in the solution with dielectric properties which are approximately equivalent to those of the living body to suppress the reflection from the surface of the object. In actual microwave CT, the influence of the diffraction from the object and the reflection from the wall of the solution tank can be ignored, because of large attenuation in the solution. To reduce an imaging time, a fan beam-type of microwave CT has been developed [2]. To realize it, many antenna elements for transmitting and receiving microwave signal are needed. To arrange antenna elements accurately along an arc in the equal interval, a technique for fabricating printed antennas on a substrate is introduced. Actually, the accuracy for arranging elements is improved by fabricating 43 printed dipoles on the curved dielectric slab. To evaluate the performance of the printed dipole, we develop a simultaneous measurement of absolute gain of antennas in the solution and dielectric properties of the solution.

First, we explain the principle and formulation of our simultaneous measurement. Next, we describe our measurement system and conditions for absolute-gain measurement of printed antenna in the solution in the frequency range of 2-3GHz. Although the diople is fed via a longish semi-rigid coaxial cable and is physically supported by it, our contrivance to position the antenna correctly in the solution is also described. After the structure of the printed dipole is described, measurement results of its absolute gain and the dielectric properties of the solution in the frequency band of 2-3GHz are shown.

### 2. Principle of Absolute-Gain Measurement

The Friis transmission formula in the lossy medium can be given, in dB, [3]

$$10\log_{10} \frac{P_r}{P_t} = -20\log_{10} R - 8.686\alpha R + A, \quad (1)$$

where  $P_r/P_t$  is the ratio of the received power to the transmitted power,  $R$  is the distance between transmitting and receiving antennas, and  $\alpha$  is attenuation constant in the medium.  $A$  is independent of the distance,  $R$ , and is given by

$$A = 20\log_{10} \left( \frac{\lambda_e}{4\pi} \right) + (G_t)_{dB} + (G_r)_{dB} - 10\log_{10}(1 - |\Gamma_t|^2) - 10\log_{10}(1 - |\Gamma_r|^2), \quad (2)$$

where  $\lambda_e$  is equivalent wavelength in the medium,  $(G_t)_{dB}$  and  $(G_r)_{dB}$  are absolute gains, in dB, of transmitting and receiving antennas, and  $\Gamma_t$  and  $\Gamma_r$  are reflection coefficients of transmitting and receiving antennas, respectively. In connecting the transmitting antenna with the port 1 and connecting the receiving antenna with port 2 of the network analyzer as shown in Figure 1, the power ratio of the left side of Eq.(1) is equal to  $|S_{21}|_{dB}$ . Then, Eq.(1) can be rewritten as follows:

$$|S_{21}|_{dB} = -20\log_{10} R - 8.686\alpha R + A. \quad (3)$$

Attenuation constant  $\alpha$  and constant  $A$  can be determined by measuring  $|S_{21}|_{dB}$  as a function of  $R$  and fitting these measured data to the curve of Eq.(3) with the least squares method. As the following

procedure, we determine the sum of absolute gains,  $(G_t)_{dB} + (G_r)_{dB}$ , in dB, from the constant  $A$ .  $|\Gamma_t|$ ,  $|\Gamma_r|$  can be obtained by measuring  $S_{11}$  and  $S_{22}$ . A phase constant of the medium,  $\beta$ , is obtained by measuring  $\angle S_{21}$  as a function of  $R$  and fitting these measured data to the straight line of the following equation:

$$\angle S_{21} = -\beta R + B, \quad (4)$$

where  $B$  is constant. Then, by definition, the equivalent wavelength is given as

$$\lambda_e = 2\pi/\beta. \quad (5)$$

Because  $|\Gamma_t|$ ,  $|\Gamma_r|$  and  $\lambda_e$  are known, the sum of absolute gains,  $(G_t)_{dB} + (G_r)_{dB}$ , in dB, can be determined from Eq.(2) as follows:

$$(G_t)_{dB} + (G_r)_{dB} = A - 20\log_{10}\left(\frac{\lambda_e}{4\pi}\right) + 10\log_{10}(1 - |\Gamma_t|^2) + 10\log_{10}(1 - |\Gamma_r|^2) \quad (6)$$

The dielectric constant  $\epsilon_r$  and conductivity  $\sigma$  of the medium can be determined as follows:

$$\epsilon_r = \frac{\beta^2 - \alpha^2}{\omega^2 \mu_0 \epsilon_0}, \quad \sigma = \frac{2\alpha\beta}{\omega\mu_0}, \quad (7)$$

where  $\omega = 2\pi f$  is the angular frequency ( $f$ :frequency),  $\mu_0$  and  $\epsilon_0$  are permeability and permittivity of free space, respectively.

We employ three-antenna method[4] to obtain the absolute gain of each antenna, that is, we prepares three antennas, we make three measurement of the sum of the gains, in dB, for three combinations. Three measurements are expressed by the following equations:

$$(G_1)_{dB} + (G_2)_{dB} = W_A, \quad (G_2)_{dB} + (G_3)_{dB} = W_B, \quad (G_3)_{dB} + (G_1)_{dB} = W_C, \quad (8)$$

where  $(G_i)_{dB}$  denotes the dB presentation of the absolute gain of  $i$  th antenna,  $W_A, W_B, W_C$  are the measured sum of the gains for the combinations 1-2, 2-3, 3-1, respectively. We can determine each gain of the antenna by solving the simultaneous equations (8).

Now, we discuss a problem when fitting measured data to the curve of Eq.(3). When two antennas are extremely close, the far field condition, which was required in deriving the Friis transmission formula, is not satisfied. Therefore, such data can not be used for curve-fitting of Eqs.(3) and (4). If a half-wavelength dipole is used, the maximum dimension of the antenna,  $D$ , is equal to  $\lambda_e/2$ . Then, the far-field boundary is given by

$$R \geq 2D^2/\lambda_e = \lambda_e/2. \quad (9)$$

For example, in the case of the deionized water at  $32^\circ\text{C}$ ,  $\lambda_e$  is equal to about 12.6mm at 2.5GHz so that we can use the measured data of  $S_{21}$  in the range that  $R \geq 6.3$  mm. On the other hand, when the distance between two antennas is somewhat larger, the value of  $|S_{21}|_{dB}$  becomes below the noise floor of the system and cannot be measured, because of large attenuation in the medium. In practice, we use the measured data of  $S_{21}$  in the range of 30mm to 70mm to avoid the logarithmic behavior of  $|S_{21}|_{dB}$  curve and the noise floor.

### 3. Measurement System and Conditions

#### 3.1 Measurement System and Conditions

The schematic of our measurement system is shown in Figure 2. The bolus tank has a 900mm diameter, 350mm height and is filled with solution of 160ℓ volume. The transmitting antenna is fixed and the receiving antenna is installed with the jigs in the stage which can be moved every 1mm by the stepper motor, which is controlled by a stage controller with a personal computer. A vector network analyzer (Agilent 8720ES) is used for  $S$  parameter measurement. First, the reference planes of port 1 and 2 are determined and the network analyzer is calibrated. Then, semi-rigid coaxial cable which is

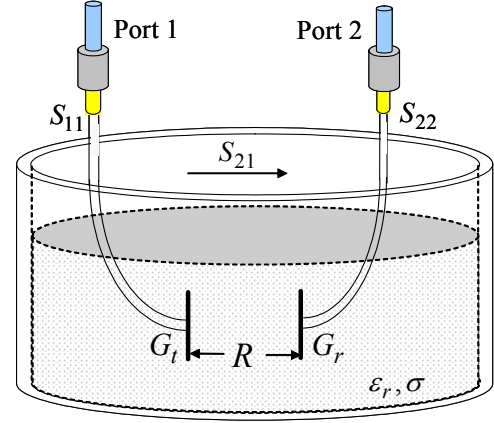


Figure 1: Transmitting and Receiving Antennas in the Solution.

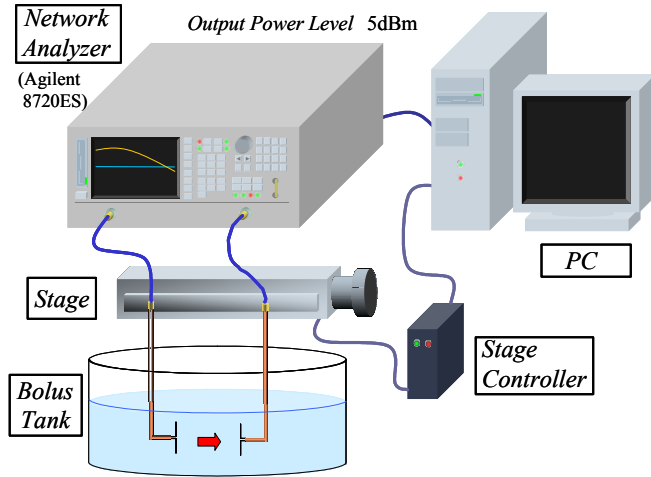


Figure 2: Measurement System

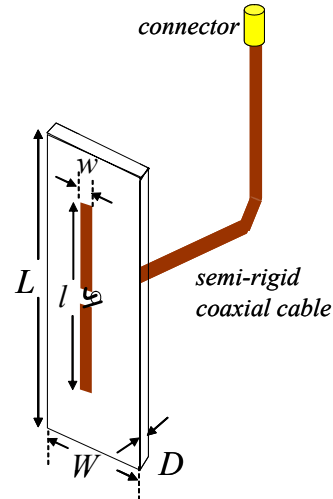


Figure 3: Printed Dipole

directly connected to the antenna is installed in each port, and the cables with antennas are immersed in the solution.  $S_{21}$  is measured in the range of  $R = 0\text{mm}$  to  $150\text{mm}$ . At  $R = 150\text{mm}$ ,  $S_{11}$  and  $S_{22}$  are measured. In the measurement, S parameters including the contribution of the semi-rigid cable are measured to avoid the connection in the solution.

As the solution, we use deionized water at the temperature of  $32^\circ\text{C}$ . Although the power must be amplified in the first stage for wide dynamic range, any amplifiers are not used in our measurement.  $5\text{dBm}$  output of the network analyzer is directly fed to the transmitting antenna through the coaxial cable with the length of  $3.25\text{m}$ , where the attenuation of about  $0.3\text{dB}$  arises.

### 3.2 Printed Dipole

A printed dipole used in our measurement is shown in Figure 3. The dipole is made on the dielectric slab by etching and the arms of the dipole are glued to the inner and outer conductors of the semi-rigid coaxial cable with the solder. The dielectric constant of the slab is equal to  $2.2$  and the slab has  $L = 45\text{mm}$  of length,  $W = 12\text{mm}$  of width and  $D = 1\text{mm}$  of thickness. The dipole has  $15\text{mm}$  of length and  $1\text{mm}$  of width. The antenna is immersed in the solution by linking the stage and the antenna with the fishing line. The larger reflection occurs when the dielectric constant of the material of the jig is quite different from that of the solution so that the fishing line is used to prevent this reflection.

## 4. Results of Measurement

### 4.1 Curve-Fitting for $|S_{21}|_{\text{dB}}$ and $\angle S_{21}$

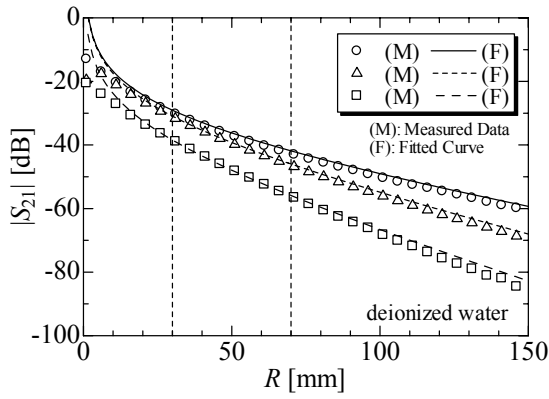
Two regression curves are obtained by fitting the data of  $|S_{21}|_{\text{dB}}$  and  $\angle S_{21}$  to Eqs. (3) and (4), as shown in Figures 4 (a) and (b). As a result, attenuation and phase constants  $\alpha$ ,  $\beta$  in the solution are determined as a function of the frequency. The sum of absolute gains of the transmitting and receiving antennas, in dB, is also obtained. In the figures, one of three curves, which can be obtained for three combinations, is depicted with resulting fitting curve. Measured and resulting curves for other combinations are almost same as the curves shown in Figure 4. Because the resulting curves are well coincided with the measured data, we can confirm that we succeed at the process of the curve fitting.

### 4.2 Dielectric Properties of the Solution

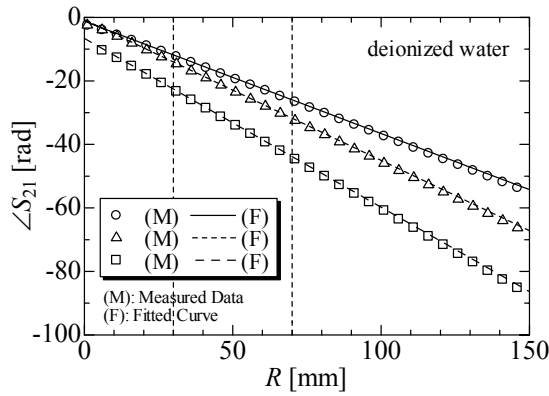
The frequency characteristics of dielectric constant and conductivity of the solution are shown in Figure 5, where empirical curves are included [5]. The figure shows the validity of our experiment for the guess of the dielectric properties of the solution.

### 4.3 Absolute Gain of the Printed Dipole

Figure 6 shows the relationship between the frequency and the absolute gains of three printed dipoles in the deionized water. In the figure, three curves are simultaneously depicted. Taking account of the slight differences of the devices, mainly due to hand-made, we can obtain the same value of absolute gains for three printed dipoles. The mean value of the gain in the frequency range of  $2\text{GHz}$  to  $3\text{GHz}$  is about  $1.5\text{dBi}$ , which is nearly equal to the directivity of the ideal half-wavelength dipole,



(a)  $|S_{21}|$  [dB]



(b)  $\angle S_{21}$

Figure 4: Curve Fitting

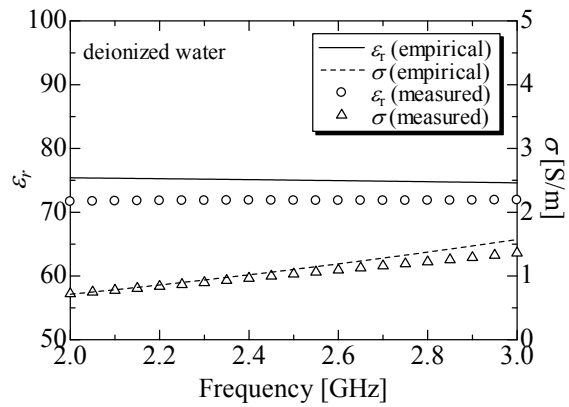


Figure 5: Dielectric Constant and Conductivity of the Solution.

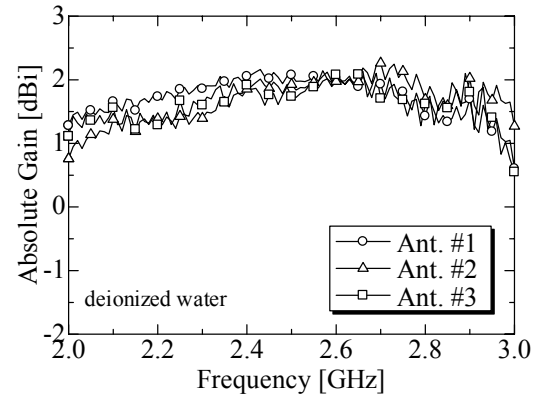


Figure 6: Absolute Gain of Each Printed Dipole in the Solution.

1.76dBi. Although the length of the printed dipole used in the measurement is much larger than a half of wavelength, the above agreement suggests the validity of our gain measurement in the solution.

## 5. Conclusion

In this paper, we report on our measurement results of absolute gain of the printed dipole, which is employed as the receiving element in the fan beam type microwave CT system. We discuss the method of measuring the absolute gain of the antenna in the solution, which is combination of modified Friis transmission formula, the curve-fitting method and the three-antenna method. We point out the problems in the measurement and show their solutions. And we measure the absolute gain of the printed dipole and compare it with theoretical value of the ideal dipole with no slab so that we can affirm the validity of our measurement method. Moreover, we show that the dielectric properties can be simultaneously obtained in our method.

## References

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