Far-Field Gain Estimation of Sandwiched Dipole Antenna in Tissue Equivalent Liquid at 5.2GHz

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***Abstract*— The authors have studied a technique for calibrating an electric-field probe used in the measurement of Specific Absorption Rate (SAR) for the mobile communication device. The probe can convert electric field intensity radiated by a reference antenna into output voltage in the tissue equivalent liquid. The measurement in the far-field region of the reference antenna is more difficult as the frequency is higher due to highly conducting loss of the liquid. The authors have proposed an extension of the Friis transmission formula which is valid in the near-field region of the antenna, set up the measurement system using a vector network analyzer with an amplifier, and then fitted measured near-field gain to the corresponding theoretical curve to estimate the absolute gain of the reference antenna. In this paper, a sandwiched dipole antenna is used as the reference antenna, and then its absolute gain is estimated at 5.2GHz. The error of measured attenuation constant cannot be ignored in the curve fitting process. A solution to remove the error of the attenuation constant is also described in this paper.**

Key words: SAR, sandwiched dipole antenna, near-field gain, Friis transmission formula

I. INTRODUCTION

It is required to develop a technique of measuring Specific Absorption Rate (SAR) in prospect of the mobile communication device at 5.2GHz. An electric-field probe is used to obtain electric-field intensity in the tissue equivalent liquid in the standard SAR measurement [1]. Therefore, a technique of calibrating the probe is required to relate the electric-field intensity radiated by a reference antenna in the liquid to its output voltage.

The probe is usually calibrated by using a waveguide system from 300 MHz – 3GHz. However, the accuracy of the calibration becomes worse as the frequency is higher because the effect of the probe diameter is not ignored. So, the authors have studied another technique of calibrating the probe by using a reference antenna operated in the liquid [2][3]. The procedure of the calibration is given as follows:

(A) To determine the absolute gain of the reference antenna in the tissue-equivalent liquid using two-antenna method.
(B) To determine the electric field intensity $|\boldsymbol{E}|$ at the distance, r, from the reference antenna.
(C) To determine the calibration factor of the probe by relating the field intensity $|\boldsymbol{E}|$ to measured output voltage.

In determining the absolute gain of the reference antenna, we adopt an extended Friis transmission formula in the liquid, which is valid in the near-field region of the reference antenna. The absolute gain is determined as the following procedure:

(A-1) To find the attenuation and phase constants α and β, by measuring complex permittivity of the liquid with the contact probe method.
(A-2) Two identical reference antennas are arranged to face each other in the liquid. S_{21} between the two antennas is measured as a function of the distance between the two antennas, r. Then, the near-field gain of the reference antenna can be estimated as a function of r.
(A-3) The near-field gain obtained above is fitted to its theoretical curve to determine the absolute gain.

Ideally, it is preferable to measure S_{21} in the far-field region of the reference antenna, because the near-field gain converges with the absolute gain in the far-field region. However, the loss in the liquid is so large that the measurement of S_{21} in the far-field region is not possible. In practice, the attenuation constant in the tissue-equivalent liquid is α = 1.33×10^{3}dB/m at 5.2GHz. Therefore, the absolute gain should be estimated by S_{21} measured in the near-field region.

Moreover, we must overcome the difficulty that the reference antenna operated in the liquid is smaller as the frequency is higher. For example, the wavelength in the liquid is 9.3mm at 5.2GHz. In this paper, a sandwiched dipole antenna, in which metallic radiator is sandwiched by two dielectric slabs, is used as the reference antenna.

II. PRINCIPLE OF ABSOLUTE GAIN CALIBRATION

A. Procedure of Calibrating Absolute Gain

As shown in Fig. 1, two reference antennas are located to face each other in the tissue-equivalent liquid surrounded by a rectangular tank. Then, transmitting and receiving antennas are connected to the ports of the vector network analyzer. When the distance between two antennas is large enough, the transmitted power is given as

$$|S_{21}(r)|^2 = (1-|S_{11}|^2)(1-|S_{22}|^2)\frac{G_1G_2e^{-2\alpha r}}{4\beta^2 r^2}, \tag{1}$$

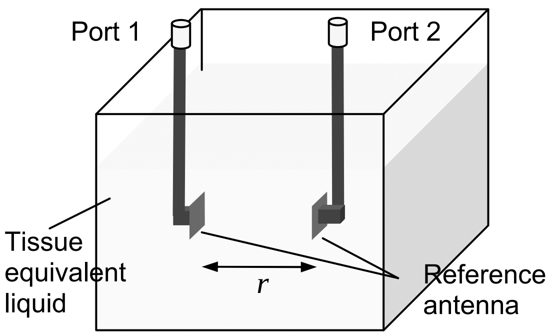

Fig. 1 Measurement system for estimating absolute gain of the identical reference antennas operated in the tissue equivalent liquid.

using the Friis transmission formula in the far-field region. $|S_{11}|$ and $|S_{22}|$ are the magnitudes of the reflection coefficient of transmitting and receiving antennas, and α and β are the attenuation and phase constants. According to two-antenna method, the condition of $G_1 = G_2 = G$ is assumed. Then, the solution of (1) under this condition defined near-field gain as

$$G_F(r) = \frac{|S_{21}(r)|e^{\alpha r} \cdot 2\beta r}{\sqrt{(1-|S_{11}|^2)(1-|S_{22}|^2)}}. \tag{2}$$

As seen from this definition, the near-field gain $G_F(r)$ would be constant in the far-field region and coincides with the absolute gain G. However, as described in the previous section, it is difficult to measure S_{21} in the far-field region. Therefore, S_{21} measured in the near-field region should be used so that the near-field gain $G_F(r)$ would be a function of the distance, r. It is necessary to extend eq. (1) to be valid in the near-field region. An extension eq. (1) is given as

$$|S_{21}(r)|^2 = (1-|S_{11}|^2)(1-|S_{22}|^2)\frac{G_1 G_2 e^{-2\alpha r}}{4\beta^2 r^2} \times \exp\left\{2\left(\frac{a_1}{r} + \frac{a_2}{r^2} + \cdots\right)\right\} \tag{3}$$

In (3), a_i is real constant which is dependent on the geometry of the antenna and the propagation constant. According to two-antenna method, the condition of $G_1 = G_2 = G$ is assumed. Then, the near-field gain can be given as

$$G_F(r) = G\exp\left\{-\left(\frac{a_1}{r} + \frac{a_2}{r^2} + \cdots\right)\right\}. \tag{4}$$

The corresponding dB representation is expressed as

$$G_{F,\mathrm{dB}}(r) = G_{\mathrm{dB}} + \sum_{i=1}^{n}\frac{A_i}{r^i}. \tag{5}$$

This is a theoretical curve for the dB representation of $G_{F,\mathrm{dB}}(r)$, where A_i is real constant. For n=2, it consists of the dB representation of the absolute gain G which is constant, the term which is inversely proportional to the distance, r, and the term which is inversely proportional to the square of the distance, r^2.

As described above, the dB representation of the absolute gain G_{dB} can be determined by the following procedure.

(A) To calculate the near-field gain by substituting measured S_{21} to eq. (2).

(B) To fit the above calculated near-field gain to its theoretical curve (5) and determine the dB representation of the absolute gain by using the least-square method.

The curve (5) is n order polynomial equation so that the related curve fitting reduces to solving the simultaneous linear equations with no initial values. However, the curve (5) is an asymptotic series expansion of the near-field gain so that we should note that ill-behavior of the series can be observed if the fitting range is incorrectly selected. For example, the regression including $1/r^2$ fails when the fitting range with no practical contribution of $1/r^2$ is selected, because of the instability of the term of $1/r^2$.

B. Error Evaluation in Determining Absolute Gain

In the above discussion, we assumed that the attenuation constant has no error. However, the uncertainty of the complex permittivity measurement using the dielectric coaxial probe (Agilent 85070E) is 5% for k=2. Therefore, in practice, the uncertainty in the attenuation constant cannot be ignored. When the error of the attenuation constant, $\Delta\alpha$ exists, the near-field gain is described as

$$\begin{aligned} G_{F,\alpha+\Delta\alpha}(r) &= B|S_{21}(r)|e^{(\alpha+\Delta\alpha)r} \cdot r \\ &= [B|S_{21}(r)|e^{\alpha r} \cdot r]e^{\Delta\alpha r} = G_{F,\alpha}(r)e^{\Delta\alpha r}, \end{aligned} \tag{6}$$

where $G_{F,\alpha}(r)$ is the near-field gain with the attenuation constant of α and B is constant which is independent of r. The dB representation of eq. (6) is expressed as

$$G_{F,\alpha+\Delta\alpha,\mathrm{dB}}(r) = G_{F,\alpha,\mathrm{dB}}(r) + 4.343\Delta\alpha r. \tag{7}$$

As the distance, r, is larger, the dB representation of the near-field gain does not converge with the dB representation of the absolute gain, but approaches to its asymptotic line, G_{dB}+ 4.343$\Delta\alpha$. For example, if the error of the attenuation constant is 2% at 5.2GHz, the error of the absolute gain at r=50mm can be estimated as 0.6dB. Therefore, the absolute gain should be estimated by including the error of the measured attenuation constant $\Delta\alpha$ in the unknown parameters. The initial values of the modified curve fitting should be selected as the estimates for the unmodified curve fitting with $\Delta\alpha$=0 in using nonlinear least-square method. Thus, the near-field gain can converge with the absolute gain as the distance is larger.

We also examine the influence of the error of the distance on the absolute gain. In this paragraph, we assume that the attenuation constant has no error. When the error of the distance, $2\Delta r$, exists, then near-field gain is approximated as

$$\begin{aligned} G_F(r+\Delta r) &= B|S_{21}(r+2\Delta r)|e^{(\alpha+2\Delta\alpha)r} \cdot (r+2\Delta r) \\ &\approx [B|S_{21}(r)|e^{\alpha r} \cdot r]e^{2\Delta\alpha r} = G_F(r)e^{2\Delta\alpha r}. \end{aligned} \tag{8}$$

The corresponding dB representation is expressed as

$$G_{F,\mathrm{dB}}(r+2\Delta r) = G_{F,\mathrm{dB}}(r) + 8.686\alpha\Delta r. \tag{9}$$

TABLE I
DIMENSIONS OF SANDWICHED DIPOLE ANTENNA

a	6.5mm	*c*	18.8mm	*e*	10.4mm
b	15mm	*d*	0.5mm	*f*	1.55mm

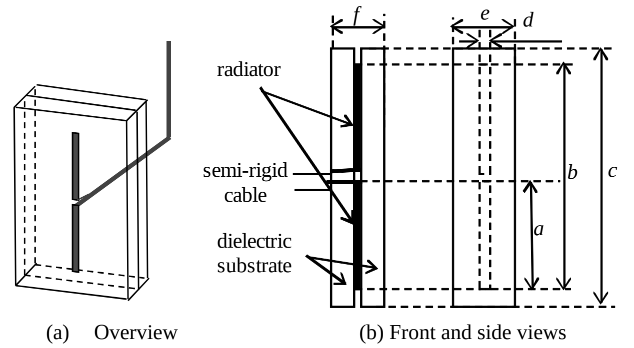

Fig. 2 Sandwiched dipole antenna.

It is directly proportional to the error of the distance $2\Delta r$. For example, the error of the absolute gain can be estimated as 0.6dB at 5.2GHz when $2\Delta r$ =1mm.

As discussed above, the errors of the measured attenuation constant and distance considerably affect the estimated absolute gain of the reference antenna operated in the liquid.

III. SANDWICHED DIPOLE ANTENNA

In this paper, a sandwiched dipole antenna which consists of printed radiator and two finite dielectric substrates as shown in Fig. 2 is used as the reference antenna[4]. The radiator is connected to the semi-rigid cable. The dimensions of this antenna operated at 5.2GHz in the tissue-equivalent liquid are shown in Table I. Because the radiator is covered with the dielectric slab, its resonant length would greatly depend upon the relative permittivity of the dielectric slab. Its dimension is larger than the antenna without dielectric cover because the relative permittivity of the dielectric substrate is much smaller than that of the liquid. This makes it easy to fabricate the antenna operated at 5.2GHz in the liquid.

IV. ESTIMATES OF ABSOLUTE GAIN

A. Attenuation and Phase Constants in Liquid

The relative complex permittivity of the tissue-equivalent liquid for 5.2GHz (NTT-AT, HT 5200) was measured by using dielectric coaxial probe (Agilent 85070E). Measured complex relative permittivity was 36.5 - j17.5 at 25.1^{o}C, then the corresponding attenuation and phase constants were α=1.33×10^{3}dB/m and β=675rad/m, respectively.

B. Measurement System of Absolute Gain

In measuring S_{21} between the two antennas, a vector network analyzer (Agilent N5230A) with a microwave amplifier (Agilent 83017A) was used. Some parameters of the network analyzer in our experiment are listed in Table II.

Two reference antennas were inserted into the liquid, where one was fixed and the other was moved with a slide stage controlled by a personal computer. The distance between the two antennas was changed from 1mm to 100mm at an interval of 1mm. In this paper, the front surface of the dielectric substrate which was not connected to the semi-rigid cable was selected as the reference plane of the reference antenna in defining the distance.

TABLE II
SOME PARAMETERS OF NETWORK ANALYZER

IF Bandwidth	30 Hz
Averaging Number	8
Sweep Type	Linear 5-6 GHz
Sweep Time	3.01 sec

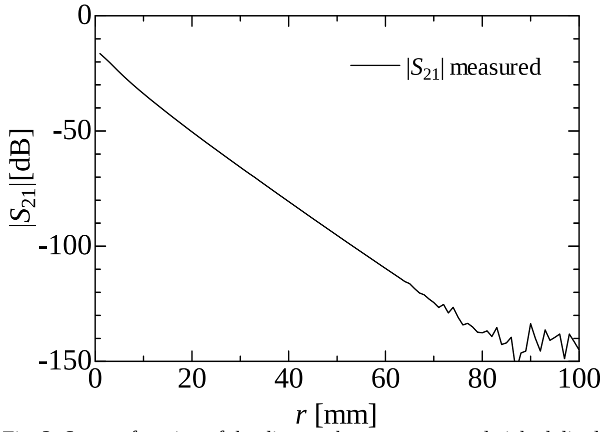

Fig. 3 S_{21} as a function of the distance between two sandwiched dipole antennas is measured by a network analyzer (Agilent N5230A) with a microwave amplifier (Agilent 83017A).

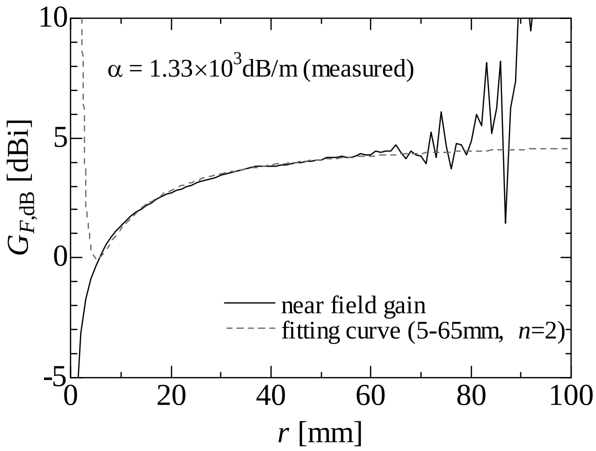

Fig. 4 Measured near-field gain and corresponding theoretical curve when measured attenuation constant α is used in the curve fitting process.

C. Measurement Results at 5.2GHz

The relationship between the distance r and measured $|S_{21}|$ is shown in Fig. 3. $|S_{21}|$ can be measured until -120dB or 65mm without noise. The relationship between the distance r and the dB representation of the near-field gain $G_{F,\mathrm{dB}}$ is shown in Fig. 4 with a solid line. In this figure, the attenuation constant is determined by measured complex relative permittivity of the liquid and is 1.33×10^{3}dB/m. $G_{F.\mathrm{dB}}$ is determined by the definition of (2) and is a function of the

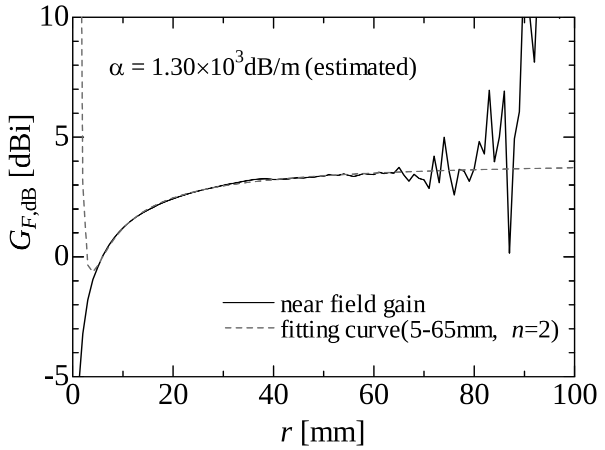

Fig. 5 Measured near-field gain and corresponding theoretical curve when the attenuation constant α is also estimated in the curve fitting process.

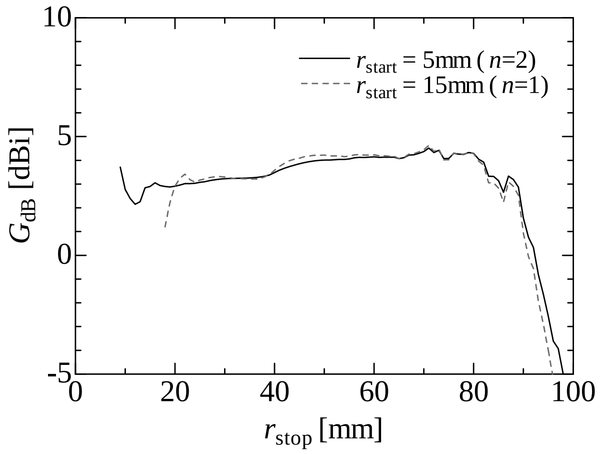

Fig. 6 Estimated absolute gain as a function of the upper limit of the fitting range, r_{stop}, if the lower limit of the fitting range, r_{start}, is fixed.

distance, r. $|S_{11}|$ and $|S_{22}|$ are measured as -12.9dB and -10.3dB, respectively. Over 60mm, $G_{F,\mathrm{dB}}$ has a fluctuation due to the noise of the measurement system. And over 70mm, the variation of $G_{F,\mathrm{dB}}$ exceeds 1dB. On the other hand, $G_{F,\mathrm{dB}}$ approaches to the line with slope as r approaches infinity. This is because measured attenuation constant would have the error, as discussed in section II. When the fitting range is selected as 5mm–65mm, unknown parameters are estimated as $G_{F,\mathrm{dB}}$ = 5.08dBi, A_1 = -5.16×10^{-2}dB·m, A_2 = 1.29×10^{-4}dB·m^2 for n=2. The estimated theoretical curve is drawn by a dotted line as shown in Fig. 4. Because the slope of the asymptotic line of the near-field gain is positive, the estimated value of the absolute gain is slightly larger than true value. To overcome the difficulty, the attenuation constant should be considered as one of the unknown parameters in the curve fitting process.

A solid line shown in Fig. 5 denotes the relationship between the distance r and the dB representation of estimated near-field gain on the condition that the attenuation constant as well as the absolute gain is determined in the curve fitting process. When the fitting range is selected as 5mm–65mm, unknown parameters are estimated as α=1.30×10^{3}dB/m, $G_{F,\mathrm{dB}}$ = 4.07dBi, A_1 = -3.55×10^{-2}dB·m, A_2 = 6.67×10^{-5}dB·m^2 for n=2. The estimated theoretical curve is drawn by a dotted line as shown in Fig. 5. The slope of the asymptotic line is zero so that estimated value of the absolute gain is considered as true value. The reason why the estimated attenuation constant is slightly smaller than measured one is the influence of the dielectric substrates which are composed of the sandwiched dipole antenna as well as the error of the complex permittivity measurement of the liquid using the dielectric coaxial probe.

Fig. 6 shows the variation of the dB representation of the absolute gain G_{dB} as a function of r_{stop} which is the upper limit of the fitting range when r_{start} which is the lower limit of the fitting range is fixed to r_{start}=5mm for n=2 and r_{start}=15mm for n=1. The reason why we select n=1 when r_{start}=15mm is to avoid ill-behavior of $1/r^2$ term as discussed in section II. Although the fluctuation of G_{dB} can be observed when the fitting range is less than 10mm, G_{dB} converges as r_{stop} is larger, as shown in Fig. 6. When we select r_{stop}=50mm, G_{dB} are 4.02dBi and 4.22dBi for r_{start}=5mm and 15mm, respectively. These values are well agreed with each other unless r_{stop} is more than 70mm, where the estimated value of the absolute gain is largely different from the true value due to the noise.

V. Conclusion

In this paper, we describe the method and show the some results on estimating the absolute gain of the sandwiched dipole antenna operated at 5.2GHz in the tissue-equivalent liquid. After reviewing the theoretical curve of the near-field gain based on extended Friis transmission formula in the liquid which is valid in the near-field region of the antennas, we examine error causes of estimating the near-field gain or the absolute gain. We must consider the errors caused by measured attenuation constant and distance which can be identified by the slope and rise/fall of the asymptotic line. Next, the absolute gain of the sandwiched dipole antenna is estimated by using a network analyzer with a microwave amplifier. We assure that it is possible to overcome the error of measured attenuation constant by treating it as one of unknown parameters in the curve fitting process. In the future, we will examine the radiation pattern of the sandwiched dipole antenna and the variation of the radiation performance due to the thickness of the dielectric slab.

Acknowledgments

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