Simulated Near-Field Gain and E-Field Intensity of Insulated Loop Antenna in the Liquid at 30 MHz

Nozomu Ishii*†, Ryosuke Takezawa*
* Graduate School of Science and Technology
Niigata University
Niigata, Japan

Lira Hamada†, and Soichi Watanabe†
† National Institute of Information and Communications Technology
Tokyo, Japan

***Abstract*—As a reference antenna operated in the tissue-equivalent liquid at 30 MHz, where the wireless communication devices are used in Japan, an insulated circular loop antenna is useful for calibrating the electric field probe for evaluating the SAR (Specific Absorption Rate) of the devices. Its near-field gain and electric field intensity are numerically simulated by the mothods of moment so that the probe can be calibrated by our formulation. Moreover, if the size of the insulated circular loop antenna is well selected, the near-field gain is approximately coincident with the far-field gain extremely in the neighborhood of the antenna and the behavior of the electric field intensity in the extremely near-field region becomes the same as that in the far-field region.**

I. Introduction

The value of SAR (Specific Absorption Rate) for the mobile communication devices operated in the GHz band should be evaluated according to the IEC standard document [1]. In general, in the frequency range of 30 MHz to 6 GHz, it can be measured by using an electric-field probe or SAR probe, which can detect the electric field intensity at the tip in the tissue-equivalent liquid [1], [2]. One of important procedures in measuring the SAR value of the devices is to calibrate the SAR probe or relate the electric field intensity detected at its tip to its output voltage so as to determine the probe sensibility or calibration factor of the probe. In the GHz band, the waveguide system or reference dipole antenna can be used to calibrate the SAR probe [1], [3]. Below 500 MHz, the probe calibration using the reference dipole antennas has an advantage over the waveguide system because the bulkiness of the waveguide is inevitable.

In contrast, for the wireless communication devices operated in 30-50 MHz band, it is also difficult to calibrate the probe by using the reference dipole antenna because of its weak radiation. However, the SAR value for the devices operated in 30-50 MHz band should be evaluated according to the IEC standard document [2]. Therefore, the authors has proposed that insulated circular loop antennas (ICLA) should be adopted as reference antennas and the corresponding near-field gain can be evaluated to predict the electric field intensity radiated by the ICLA for the SAR probe calibration [4].

In this paper, after some required expressions to describe the power transmission in the liquid are reviewed, we show some numerical results of the near-field gain and corresponding electric field intensity in the extremely near-field region as a function of the distance, calculated by using methods of moment (MoM) which can analyze the wire-structure in the liquid, and examine the existence of the optimized size for the ICLA at 30 MHz.

II. Estimation of Near-Field Gain in the Liquid

A. Extended Friis Transmission Formula

The tissue-equivalent liquid at 30 MHz defined by the IEC standard document has the dielectric constant of 55 and conductivity of 0.75 S/m [2]. In this liquid, the wave travels and decays with the attenuation constant of $\alpha = 77.3$ dB/m and the effective wavelength of $\lambda_e = 627$ mm, respectively. In the liquid container, the only way to calibrate the SAR probe is to measure the near-field gain and electric field intensity of the reference antenna in the extremely near-field region, because of the physical limitation and larger wavelength in the liquid. Therefore, it is impossible to apply the conventional Friis transmission formula with the attenuation factor in the liquid which is valid in the far-field region for evaluating the near-field gain so that the Friis transmission formula should be extended so as to be valid in the near-field region as the authors has proposed [5]. The power transmission between the identical antennas #1 and #2, $|S_{21}|^2$ can be given as

$$|S_{21}|^2 = (1-|S_{11}|^2)(1-|S_{22}|^2)\frac{G_f^2\exp(-2\alpha r)}{4\beta^2 r^2} \times \exp\left\{2\left(\frac{a_1}{r}+\frac{a_2}{r^2}+\cdots\right)\right\}. \quad (1)$$

where S_{11} and S_{22} are the reflection coefficients of antennas #1 and #2, respectively. G_f is the far-field gain of the antennas #1 and #2, $\beta = 2\pi/\lambda_e$ is the phase constant in the liquid, and r is the distance between the antennas #1 and #2. In the near-field region, an additional factor with real constants $a_1, a_2, \cdots$, is essentially significant in the liquid.

B. Near-Field Gain

By the two-antenna method which is one of methods to determine the gain, the antennas #1 and #2 have identical gain as assumed in (1). Then, the near-field gain can be defined as

$$G_n(r) = \frac{|S_{21}(r)|\exp(\alpha r)\cdot 2\beta r}{\sqrt{(1-|S_{11}|^2)(1-|S_{22}|^2)}}. \quad (2)$$

It can be also expressed as

$$G_{n,\mathrm{dB}}(r) = G_{f,\mathrm{dB}} + \frac{A_1}{r} + \frac{A_2}{r^2} + \cdots, \quad (3)$$

Copyright 2014 IEICE

where $A_1, A_2, \cdots$ are real constants [5]. The near-field gain in the dB representation, $G_{n,\mathrm{dB}}$, is composed of the far-field gain in the dB representation, $G_{f,\mathrm{dB}}$ and an asymptotic series in the inverse powers of the distance, r.

To determine the near-field gain of the reference antenna, first, the attenuation and phase constants, α and β, in the liquid are measured by using the contact probe method. Second, S parameters between the antennas #1 and #2 are measured as a function of the distance, r, then the near-field gain is evaluated according to its definition (2). Note that the reflection coefficients S_{11} and S_{22} should be measured as a function of the distance in the extremely near-field region.

III. Expression for E-Field Intensity in the Extremely Near-Field Region

According to the IEC standard document [1], the electric field intensity radiated by the reference antenna is given as

$$|\boldsymbol{E}_f(r)| = \left[\frac{30P_{in}(1-|\Gamma_t|^2)G_f}{\mathrm{Re}(\sqrt{\dot{\varepsilon}_r})}\right]^{1/2}\frac{\exp(-\alpha r)}{r}. \quad (4)$$

where P_{in} denotes the input power, Γ_t denotes the reflection coefficient of the reference antenna, $\dot{\varepsilon}_r$ is complex relative permittivity in the liquid. The far-field gain, G_f can be calculated by the numerical simulation, for example, MoM, but cannot be evaluated by using the measured S parameters.

To solve the above difficulty, we has proposed a modified expression for the electric field intensity radiated by the reference antenna in terms of the near-field gain, $G_n(r)$ [6]. The modified expression can be obtained by only replacing the far-field gain, G_f, with the near-field gain, $G_n(r)$ in (4):

$$|\boldsymbol{E}_n(r)| = \left[\frac{30P_{in}(1-|\Gamma_t|^2)G_n(r)}{\mathrm{Re}(\sqrt{\dot{\varepsilon}_r})}\right]^{1/2}\frac{\exp(-\alpha r)}{r}. \quad (5)$$

Therefore, the near-field gain, $G_n(r)$ and electric field intensity $|\boldsymbol{E}_n(r)|$ can be evaluated only using measured S parameters as a function of the distance between the two identical reference antennas, r, with no use of the far-field gain, G_f.

IV. Simulated Near-Field Gain and E-Field Intensity of ICLA in the Liquid

A. Outline of Simulation

Using Richmond's code [7], which is well known as a form of MoM and can analyze thin-wire structures in the lossy homogeneous medium, for example, in the liquid, the power transmission between the two identical insulated wire antennas, S_{21} and the reflection coefficients of the two antennas, S_{11}, S_{22} can be calculated. In our calculation, the ICLA is modeled by a regular hexadecagon (regular convex 16-gon), with the circumference, C, the wire radius of 1 mm and the wire conductivity of 5.8×10^7 S/m. The wire is assumed to be covered with the waterproof insulation, which has the thickness of 0.2 mm and dielectric constant of 3.2. The dielectric property of the tissue-equivalent liquid for 30 MHz is described in the IEC standard document as explained before. As shown in Fig. 1, the two reference antennas are faced in the liquid as their central axes and directions of the feed points are coincident with each other.

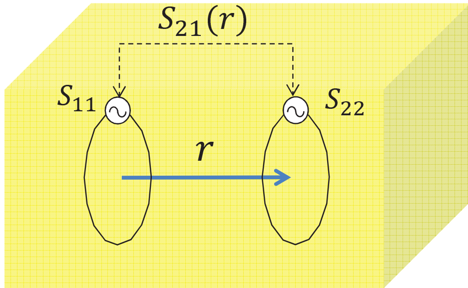

Fig. 1. The Position and Distance for Two Insulated Circular Loop Antennas (ICLAs) Faced in the Tissue-Equivalent Liquid to Calibrate the Near-Field Gain

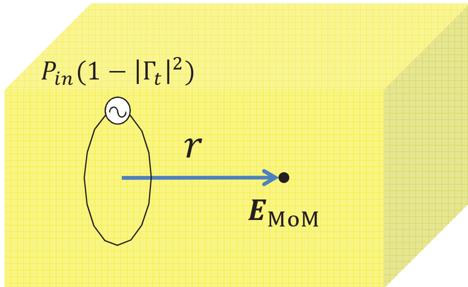

Fig. 2. Geometry for Calculating Electric Field Intensity Radiated by an Insulated Circular Loop Antenna (ICLA) by Richmond's code

Also, the electric field intensity in the extremely near-field region of the reference antennas can be rigorously calculated by this code. In our simulation, the electric field intensity is evaluated on the central axis of the ICLA as shown in Fig. 2.

The code can simulate the S parameters between the two ICLAs, which should be measured in the experiment for the SAR probe calibration, as well as the far-field gain of the ICLA, which cannot be evaluated by using measured S parameters, and so on. However, the near-field gain of the ICLAs, evaluated by using the S parameters in the extremely near-field region, can be compared with the far-field gain so that we can validate our proposed formulation of the near-field gain and electric field intensity, described above.

In the following, we also focus attention on the magnitude of the wave impedance, $\eta_{\mathrm{MoM}}(r) = |\boldsymbol{E}_{\mathrm{MoM}}(r)|/|\boldsymbol{H}_{\mathrm{MoM}}(r)|$, where $|\boldsymbol{E}_{\mathrm{MoM}}(r)|$ and $|\boldsymbol{H}_{\mathrm{MoM}}(r)|$ are electric and magnetic field intensities radiated by the ICLAs, which can be calculated by using MoM, to examine the behavior of the fields extremely in the neighborhood of the ICLAs. η_{MoM} can be compared with the real part of the intrinsic impedance in the liquid, which can be given as $\eta_{\mathrm{re}} = 120\pi/\mathrm{Re}(\sqrt{\dot{\varepsilon}_r})$. Obviously, η_{MoM} converges with η_{re} in the far-field region of the ICLAs.

B. Simulated Results

Fig. 3 shows the near-field gain of three ICLAs with the circumference of C = 400 mm, 478 mm, and 600 mm as a function of the distance between the two antennas. It also shows the far-field gain calculated by MoM. As C is larger, the slope of the near-field gain is larger for $r = 100$ mm. The slope is negative for $C = 400$ mm and positive for $C = 600$ mm. For $C = 478$ mm, the near-field gain can converge with a flat

Copyright 2014 IEICE

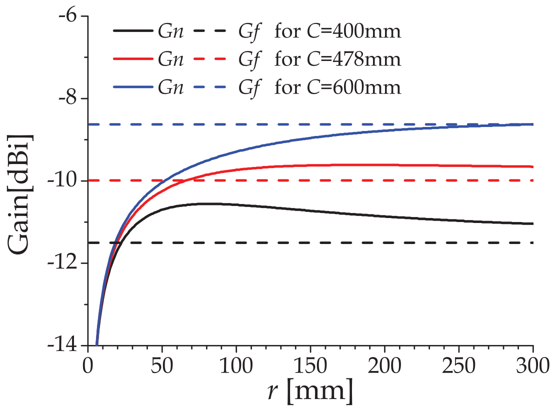

Fig. 3. Distance Dependence of Simulated Near- and Far-Field Gain of the Insulated Circular Loop Antenna (ICLA) with the circumference of $C =$ 400 mm, 478 mm, and 600 mm in the Tissue-Equivalent Liquid at 30 MHz

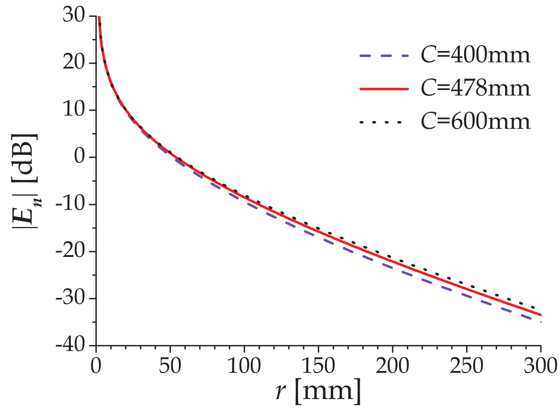

Fig. 5. Distance Dependence of Simulated Electric Field Intensity, $|\boldsymbol{E}_n(r)|$, defined as (5), of the Insulated Circular Loop Antenna (ICLA) with the circumference of $C = 400$ mm, 478 mm, and 600 mm in the Tissue-Equivalent Liquid at 30 MHz

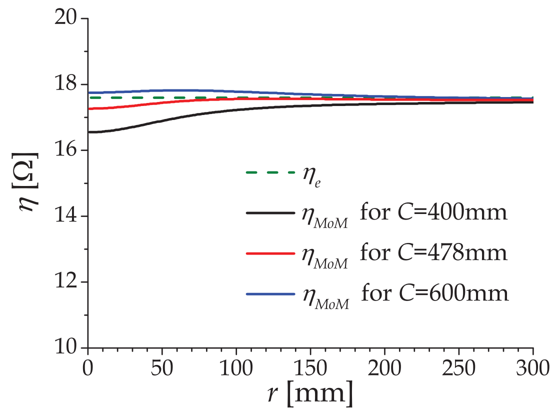

Fig. 4. Distance Dependence of Simulated Wave Impedance of the Insulated Circular Loop Antenna (ICLA) with the circumference of $C = 400$ mm, 478 mm, and 600 mm in the Tissue-Equivalent Liquid at 30 MHz

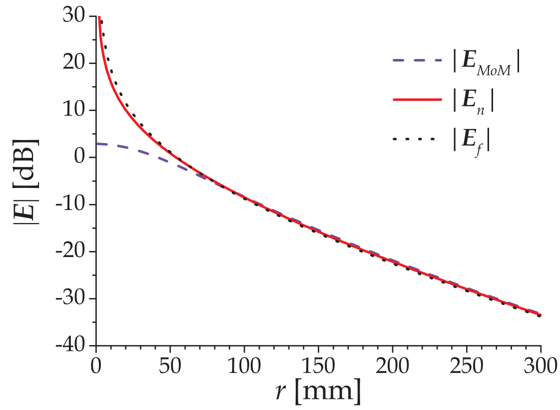

Fig. 6. Distance Dependence of three types of Simulated Electric Field Intensity, $|\boldsymbol{E}_{\text{MoM}}(r)|$, $|\boldsymbol{E}_n(r)|$, and $|\boldsymbol{E}_f(r)|$, of the Insulated Circular Loop Antenna (ICLA) with the circumference of $C = 478$ mm in the Tissue-Equivalent Liquid at 30 MHz

line, with the value of -9.7 dB, whereas the far-field gain is -10.0 dB. The difference between the near- and far-field gains is only 0.3 dB for $r = 100$ mm so that the near-field gain can behave in much the same way as the far-field gain if C is well selected.

The similar tendency can be observed from the wave impedance. Fig. 4 shows the wave impedance as a function of the distance, $\eta_{\text{MoM}}(r)$, for the above three ICLAs and the real part of the intrinsic impedance in the liquid, η_{re}. For $C = 478$ mm, the difference between η_{MoM} and η_{re} is 0.2% at $r = 100$ mm and 0.3% at $r = 200$ mm. This fact means that the behavior of the fields radiated by the ICLA in the extremely near-field region is similar to that in the far-field region, if C is well selected.

Fig. 5 shows the electric field intensity as a function of the distance, $|\boldsymbol{E}_n(r)|$, defined in (5) for three ICLAs. Predictably, the ICLA has larger electric field intensity as C is larger, because of the larger loop area. Fig. 6 shows three types of the electric field intensity, $|\boldsymbol{E}_{\text{MoM}}(r)|$, $|\boldsymbol{E}_n(r)|$, and $|\boldsymbol{E}_f(r)|$ as a function of the distance for $C = 478$ mm. There is an apparent discrepancy between $|\boldsymbol{E}_{\text{MoM}}(r)|$ and $|\boldsymbol{E}_n(r)|$ for $r \leq 70$ mm, for example, the difference is 2 dB at $C = 50$ mm. Conversely, $|\boldsymbol{E}_n(r)|$ is approximately coincident with $|\boldsymbol{E}_{\text{MoM}}(r)|$ for $r \geq 70$ mm, for example, the difference is 0.1 dB at $r = 100$ mm. The difference between $|\boldsymbol{E}_n(r)|$ and $|\boldsymbol{E}_f(r)|$ is about 0.25 dB for $r \leq 300$ mm, however, $|\boldsymbol{E}_n(r)|$ can exactly converge with $|\boldsymbol{E}_f(r)|$ in the far-field region of the ICLA because $G_n(r)$ also does converge with G_f in the far-field region. The above observation leads to the constant near-field gain and the electric field intensity which decreases as the inverse square of the distance with the exponential decay if the size of the ICLA is well selected. This fact is made easy to measure the near-field gain and electric field intensity of the optimized ICLA in the extremely near-field region as well as in the far-field region.

Copyright 2014 IEICE

V. Conclusion

To calibrate the SAR probe in the tissue-equivalent liquid at 30 MHz, the insulated circular loop antenna is one of strong candinates for the reference antenna, because it takes in the same distance dependence as the reference dipole antenna used in the GHz band, if its size is well selected. To realize the SAR probe calibration using it as the reference antenna, the above fact should be validated by experiment.

Acknowledgment

This work was partly supported by the Ministry of Internal Affairs and Communications in the government of Japan and Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science.

References

[1] IEC International Standard 62209-1, "Human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices — Human models, instrumentation, and procedures — Part 1: Procedure to determine the specific absorption rate (SAR) for hand-held devices used in close proximity to the ear (frequency range of 300MHz to 3GHz)," Feb. 2005.

[2] IEC International Standard 62209-2, "Human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices — Human models, instrumentation, and procedures — Part 2: Procedure to determine the specific absorption rate (SAR) for wireless communication devices used in close proximity to the human body (frequency range of 30MHz to 6GHz)," Mar. 2010.

[3] N. Ishii, Y. Miyota, K. Sato, L. Hamada, and S. Watanabe, "SAR-probe calibration system using reference dipole antenna in tissue-equivalent liquid," IEICE Trans. Commun., vol. E95-B, no. 1, pp. 60-68, Jan. 2012.

[4] N. Ishii, R. Takezawa, H. Toyoshima, L. Hamada, and S. Watanabe, "Optimal size of waterproofed shielded loop antenna in a tissue-equivalent liquid to calibrate SAR probe in HF band," Abst. PIERS 2013 Stockholm, p. 750, Stockholm, Sweden, Aug. 2013.

[5] N. Ishii, T. Akagawa, K. Sato, L. Hamada, and S. Watanabe, "A method of measuring gain in liquids based on the Friis transmission formula in the near-field region," IEICE Trans. Commun., vol. E90-B, no. 9, pp. 2401-2407, Sep. 2007.

[6] N. Ishii, H. Toyoshima, L. Hamada, and S. Watanabe, "E- and H-fields' representation extremely near small waterproofed loop antenna in the liquid," Proc. 2013 Korea-Japan Workshop on Antennas and Propagation, p. 16, Gwangju, Korea, Jan. 2013.

[7] J. H. Richmond, "Computer program for thin-wire structure in a homogenious conducting medium," Nat. Tech. Inform. Service, Rep. NASA CR-2399, 1975.

Copyright 2014 IEICE