Capsule Antenna Design Based on Transmission Factor Through Human Body

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Abstract: To design antennas for ingestible capsule endoscope systems, the transmission factors of a dipole to dipole and a loop to loop antennas through homogenous human body phantom are investigated by numerical and experimental study. The S-parameter method is used to evaluate transmission characteristics through a torso-shaped phantom in a broadband frequency range. Good agreement of S-parameters between measured results and numerical analysis is observed and the transmission factors for both cases are obtained. Comparison of the transmission factors between HBEL and deionized water is presented to explain the relation between conductivity and the transmission characteristics. Two types of antennas, dipole antennas and loop antennas are compared. In the case of dipole antenna placed in deionized water, it has been observed that the transmission factor decreases as conductivity increases. On the other hand, there is a local maximum in the transmission factor at 675 MHz in the case of HBEL. This phenomenon has not been observed in the case of loop antennas. The transmission factor of capsule dipole system and capsule loop system are compared and the guideline in designing capsule antennas by using transmission factor is also proposed.

Keywords: Capsule antenna, conjugate matching condition, transmission factor, dipole antenna, loop antenna

1. Introduction

Wireless capsule endoscope system has gained popularity in health-care applications [1-3]. The system uses a wireless transceiver to obtain medical images of the inside of the human body [1]. Generally, a capsule has a maximum length of 20 mm and a maximum diameter of 10 mm [1], and it is considered that the transmitting power of antennas is extremely low caused by its physical size. Furthermore, the absorption of electromagnetic waves by the internal organs is quite large caused by high conductivity of the internal organs with frequency dependent characteristics.

Selection of antenna type such as dipole antenna or loop antenna is important to decrease propagation loss between the capsule antenna and the antenna outside of the human body. Finding a suitable frequency band for high efficiency transmission for the capsule endoscope system is important.

Estimation of the RF-link budget is essential in the capsule endoscope communication systems. Path loss through the human body was presented by several different expressions [4-7]. In [4], the electric field attenuation along the coordinate axes was used to express path loss. The receiving antenna was considered in [5] and S_{21} was used to express the path loss. In [6], the difference of S_{21} with and without the human body was used for the definition of transmission loss.

In our previous research [8], a dipole antenna placed in a phantom filled with lossy liquid was studied. The impedance matching was obtained at a frequency, also a large value of S_{21} was observed. The experimental results are agree with the calculated results, however, the study concerning the path loss was not carried out. In

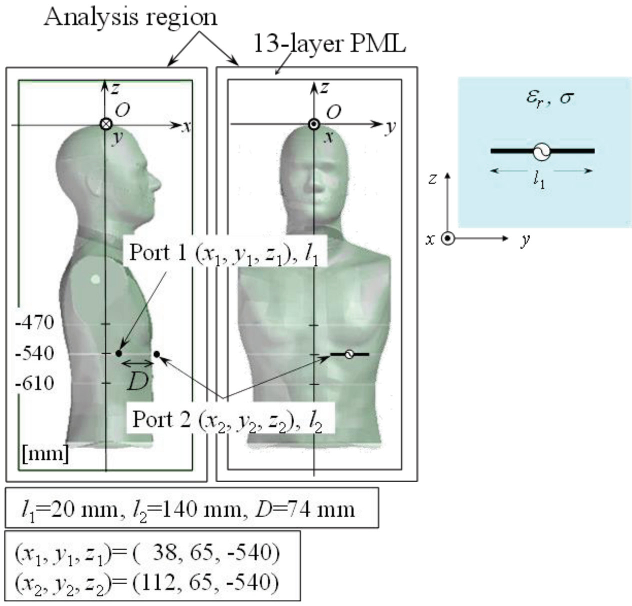

Figure 1: Human torso-shaped model with dipole antennas.

[9], the path loss has been studied in an in-homogeneous model and only the numerical results were presented, however, it is difficult to perform the experiment in an in-homogeneous real human body model.

In this report, a pair of dipole and loop antenna was placed inside and outside a torso-shaped phantom used in [8], respectively, and the transmission factor was evaluated by both the numerical and the experimental method. The FDTD (Finite-Difference Time-Domain) analysis with considering frequency dependent dielectric permittivity was used as the numerical analysis. The transmission factor is the relative maximum received power under the condition that the complex-conjugate matching conditions are satisfied at both transmitting and receiving ports. The transmission factors of a dipole and a loop antenna immersed in two kinds of homogeneous liquid are studied to frequency independence on the propagation loss and to obtain the suitable operating frequency.

2. Experiment setup and FDTD analysis

Figure 1 shows the numerical model and the experimental setup, respectively. A human torso-shaped phantom developed by SPEAG [10] was used as the container of liquid. A dipole antenna with length l_1 was placed inside the torso phantom at the position indicated as Port 1(x_1, y_1, z_1), which is chosen as a typical position of the stomach in the human body. And a dipole antenna with length l_2 was placed outside of the torso phantom as Port 2. The distance between the antennas was set to D=74 mm. S-parameters of dif-

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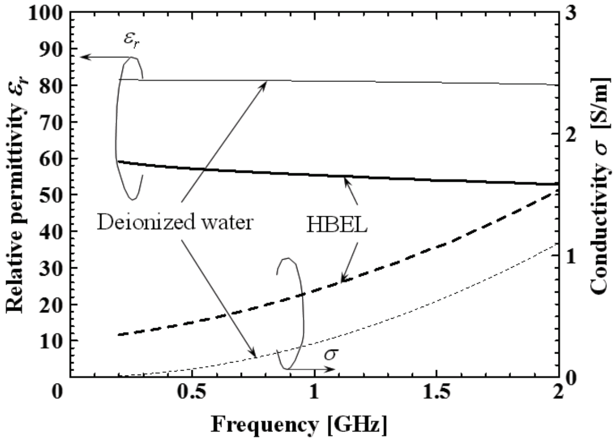


Figure 2: Relative permittivity and conductivity of deionized water and HBEL.

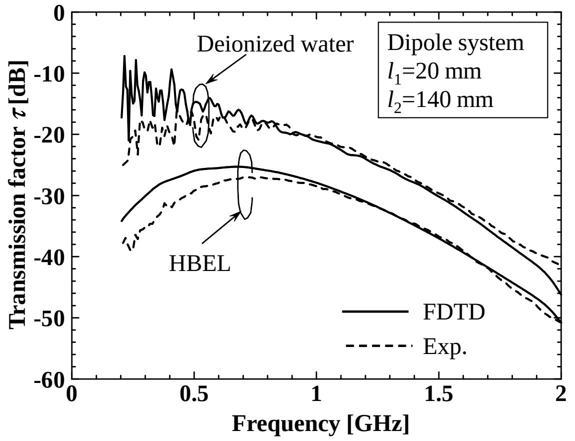


Figure 4: Transmission factor τ of dipole antennas through torso-shaped phantom.

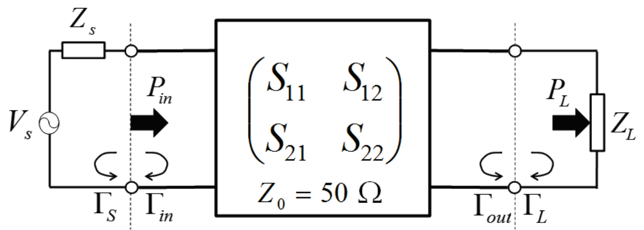


Figure 3: Two-port equivalent circuit.

ferential mode were measured by using four-port Vector Network Analyzer (Keysight N5224A) in order to compare with the numerical results in the broadband frequency range.

The in-homogeneous real human body was studied numerically in [9], deionized water and a human body equivalent liquid (HBEL) were filled in the torso-shaped phantom. In the FDTD analysis, the number of cells is 202×304×462, the Gaussian differential pulse is used as an excitation. Subgridding technique was used and the cell sizes are Δx=Δy=Δz=2 mm for the human torso-shaped phantom and Δx=Δy=Δz=1 mm for the antennas. 13-layer PML was used as an absorbing boundary condition. To simplify the investigation, the ohmic loss of the antennas were ignored .

Figure 2 shows the measurement results of relative permittivity and conductivity of the deionized water and HBEL by using the coaxial probe method. In the measurement, the torso-shaped phantom was filled with the deionized water and HBEL with a temperature of 18 ° C.

3. Transmission factor through human body phantom

Two-port network equivalent circuit is shown in Figure 3 [12]. Transmitting antenna is connected to a source with an internal impedance of Z_S, while receiving antenna is loaded with an internal impedance of Z_L. P_L is the power delivered to the load Z_L, P_{in} is the input power, P_{inc} is the incident power, Γ_S and Γ_L are the reflection coefficients looking toward the source Z_S and the load Z_L, respectively. The transmission factor τ is defined by using S-parameters of the circuit as:

$$\begin{aligned}\tau &= \left.\frac{P_L}{P_{inc}}\right|_{Z_S=Z_{in}^*, Z_L=Z_{out}^*} = \frac{P_L}{P_{in}} \\ &= \frac{1}{1-|\Gamma_S|^2}|S_{21}|^2\frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2}.\end{aligned} \tag{1}$$

Figure 4 shows the transmission factor τ of dipole antenna through a torso-shaped phantom filled with HBEL. In the case of dipole antenna placed in deionized water, In the case of HBEL with higher conductivity compared to the deionized water, a local maximum with level of -25.3 dB was observed at 675 MHz corresponding to the half-wavelength resonant frequency (l_1=$\lambda_g/2$) of dipole antenna immersed in HBEL.

The rectangular loop antenna was also studied to compare with the results of dipole antenna. Figure 5 shows the model a torso-shaped phantom with a pair of loop antennas. A rectangular, 1-turn loop antenna with loop length of L_1=40 mm was immersed in HBEL as Port 1, and a rectangular loop antenna with loop length of L_2=280 mm was placed outside the phantom as Port 2. Figure 6 shows the transmission factor τ in the case of loop antenna immersed in HBEL. A good agreement was obtained between the experiment and the FDTD analysis.

4. Capsule antenna design

In this section, an example of capsule antenna design by using the transmission factor τ is presented. The antennas were enclosed by the rectangular column capsule as shown in Figure 7. The rectangular shaped capsule was used because it is simple and easy to be calculated in the FDTD analysis. Dimension of the rectangular column capsules are with length of 30 mm and width of 10 mm. To simplify the investigation, relative permittivity of capsule is set as the air (ε_r=1). In the case of capsule loop antennas, the antennas and the phantom are with

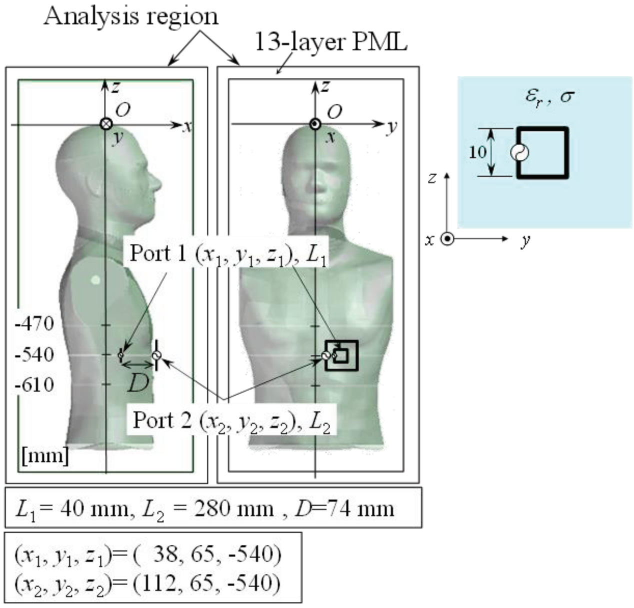


Figure 5: Human torso-shaped model with loop antennas.

the same structure as shown in Figure 1 and Figure 5, except for the presence of a rectangular column capsule.

Figure 8(a) shows the transmission factor τ, and Figure 8(b) shows the relative received power of capsule dipole system and capsule loop sytem through torso-shaped phantom, respectively. In the case of capsule dipole system, it has been found that there is a local maximum of the transmission factor τ at a frequency, which is also observed in the case without the capsule enclosure. As an example of the internal impedances, Z_S=4.91+j2248.6 Ω and Z_L=18.6+j467.2 Ω can be selected and it can be used as the external matching circuits. It is noted that large value of τ=-21.6 dB at 490 MHz is observed which is 3.7 dB larger than the case shown in Figure 4 at 695 MHz. This increment of the transmission factor τ is considered that the feeding point of dipole antenna is not contact to the lossy liquid by the presence of a capsule enclosure.

In the case of capsule loop system, the transmission factor decreases as frequency increases monotonously. Under the conditions Z_S=0.03-j19 Ω and Z_L=14.9-j370 Ω, a large value of τ=-14.7 dB was obtained at the lowest frequency of 200 MHz. This phenomenon is caused by the strong magnetic-coupling between two loop antennas in the near-field region, while this phenomenon was not appeared between two dipole antennas. It is considered that loop system is preferred to realize high efficiency power transfer in the low frequency range, while the transmission factors of both the dipole system and the loop system are almost the same in the high frequency range.

5. Conclusion

In this research, EM-wave propagation through a human body phantom was studied in the frequency range 200 MHz to 2 GHz. The transmission characteristics of a dipole antenna and a loop antenna immersed in the torso-shaped phantom filled with human body equivalent liquid were investigated by the FDTD analysis and the measurements.

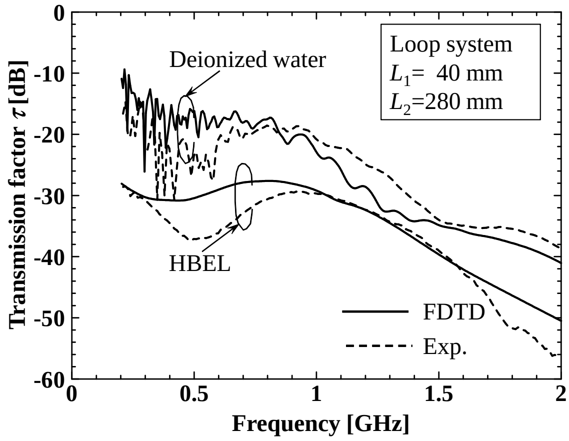
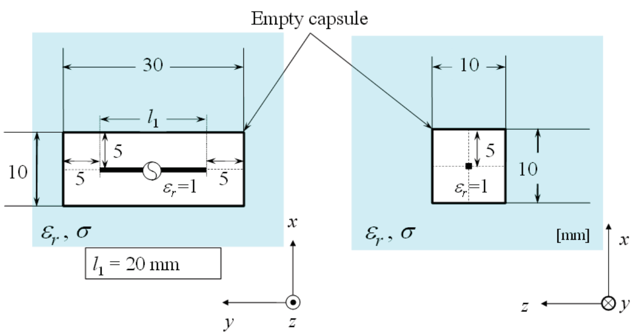
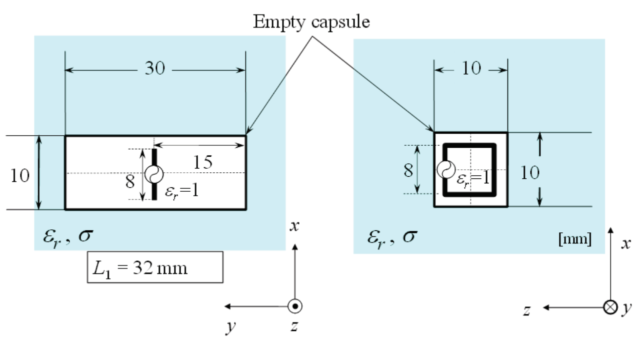


Figure 6: Transmission factor τ of loop antennas through torso-shaped phantom.

Good agreement between measured and calculated results was observed. The transmission factor τ was used to evaluate the path loss through the human body phantom. It has been found that there is a local maximum of the transmission factor τ at a frequency in the case of HBEL. Also it is found that this phenomenon is not observed in the case of the loop antenna.

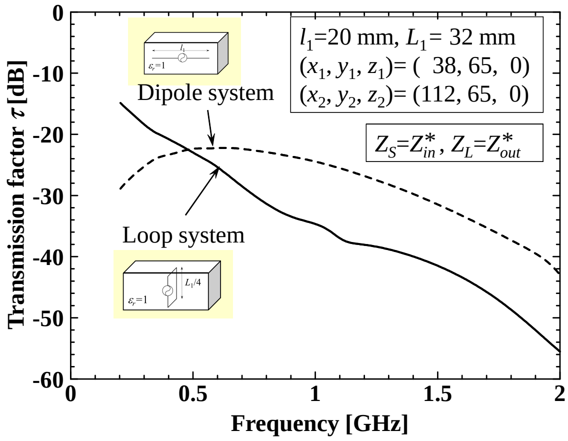


(a) Capsule dipole antenna.

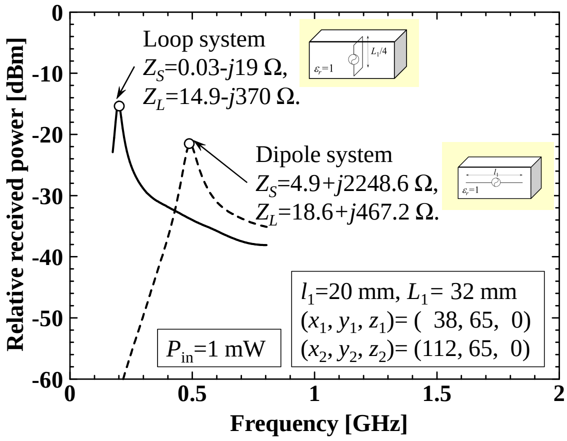


(b) Capsule loop antenna.

Figure 7: Structure of capsule antennas.



(a) Transmission factor τ.



(b) Relative received power.

Figure 8: Transmission factors and relative received power of capsule dipole and loop antennas through torso-shaped phantom.

The effect of capsule enclosure was discussed by using the transmission factor τ and design of capsule antennas has been performed with several guidelines as follows: the local maximum of the transmission factor around 600 MHz appears when used antennas are dipole type. Lower frequency should be used to obtain large value of the transmission factor τ when used antennas are loop type. In practical use of these guidelines for the application of ingestible capsule endoscope, the results in this study are considered applicable even in the cases when the geometry of capsule antenna becomes complex.

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