Broadband Measurement of Complex Permittivity for Liquids Using the Open-ended Cut-off Circular Waveguide Reflection Method

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Abstract— Various studies on specific absorption rates (SARs) have been carried out with liquid phantoms representing human body tissues in the field of electromagnetic compatibility (EMC) research. As a faithful representation of human body tissue is needed to establish an accurate SAR for measurement, knowledge regarding the precise measurement of sample materials with high permittivity and high loss is very important. In this study, the complex permittivity of a liquid phantom material was measured using the open-ended cut-off circular waveguide reflection method. The effectiveness of the proposed approach for measuring a liquid phantom with high permittivity and high loss was also confirmed by comparing the measurement results with those obtained using the TM_{010} circular cavity resonator method.

1. INTRODUCTION

In response to recent health concerns regarding the application of electromagnetic waves to the human body, the effects of such waves and methods for measuring complex permittivity in relation to liquids used for humanoid phantoms have been studied [1].

Meanwhile, the development of techniques for creating new chemical materials based on exposure to electromagnetic waves has accelerated. In research on such microwave chemistry applications, liquids are generally used as solvents for the synthesis of new chemical materials. Accordingly, knowledge of exact material constants for objects to be heated in the frequency band of electromagnetic wave exposure is very important.

In general, reflection constant determination method using a coaxial probe is a popular technique for measuring the complex permittivity of liquids [2]. Although this method readily supports broadband estimation of material constants for liquids, a large amount of water is needed to avoid the influence of reflective waves from the vessel bottom. The cavity resonator method can also be used for high-precision measurement [3–5]. A transmission constant determination technique involving the insertion of a liquid sample into a Teflon tube with a waveguide can be used for measurement at a continuous frequency [6]. A cross-shaped coaxial probe can be used for simple measurement of complex permittivity, but material constant data on a known material is required as a standard with this approach [8]. A transmission constant determination method involving the insertion of sample materials into a coaxial line [7] and a reflection constant determination method involving the insertion of sample materials into a cylindrical cavity [9] can be adopted for broadband measurement.

In this study, the complex permittivity of tap water, methanol, ethanol (99.5) and isopropanol with high permittivity and high loss was measured via the reflection method using a coaxial feed open-ended cut-off circular waveguide [10] to reduce the effects of liquid spillage at the time of sample material insertion. The effectiveness of the proposed method was then evaluated by comparing its results with those of the TM_{010} cylindrical cavity resonator method [4]. Next, the complex permittivity of the liquids was measured at frequencies ranging from 50 MHz to 3.0 GHz using the procedure outlined above. In this case, the measurement limit was set at a very low frequency.

2. MEASUREMENT PROCEDURE

The liquid phantom was measured using the method outlined here.

1. Calibration of S_{11} (input impedance) is performed at the tip of a coaxial line before mounting on the measurement jig.
2. The jig is attached to a measurement cable connected to a network analyzer (see Figs. 1 and 2).
3. Complex permittivity is measured at the front of the sample material when it is inserted into the network analyzer.

4. The complex permittivity of the sample material is estimated based on an inverse problem to coincide with the calculated input impedance and the result of input impedance measurement.

The measurement jig for liquid insertion is made from a cut piece of worked brass and an SMA connector. S_{11} calibration must be performed under a condition in which the measurement jig is not mounted when input impedance is measured using a network analyzer. The reference plane is then moved using a VNA electrical delay function so that the input impedance is $\infty\Omega$ on the Smith chart when the measurement jig is attached. When actual measurement is made, a coaxial line attenuator (6 dB) is connected to the front of the measurement jig to reduce the influence of reflection waves on the measurement results with this setup (Figure 2). In addition, the complex permittivity of the inserted sample material must be estimated from the measured input impedance as an inverse problem. This work is performed using the 2D Newton-Raphson method.

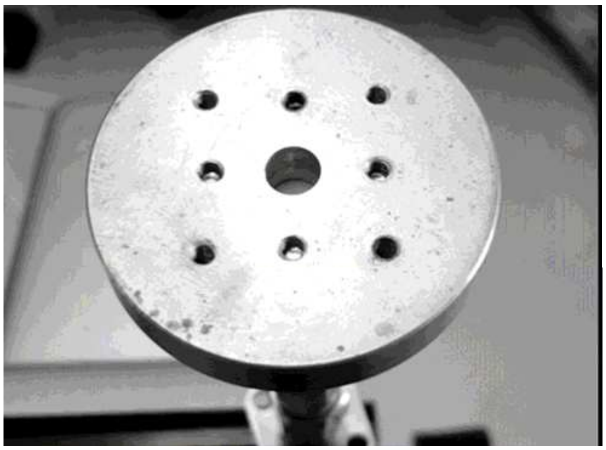

Figure 1: Measurement jig.

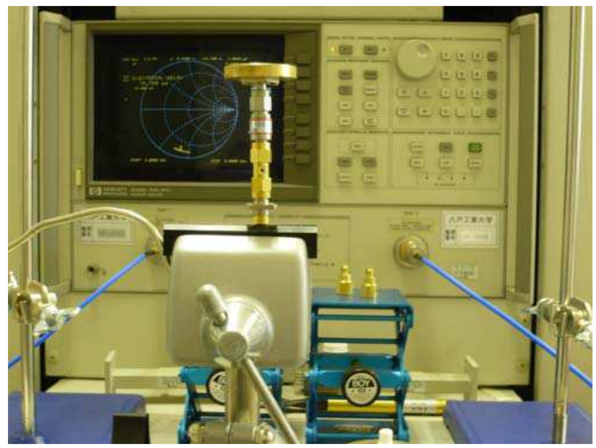

Figure 2: Measurement setup.

3. CALCULATION OF INPUT IMPEDANCE

In the proposed method, input impedance at the reference plane (as seen from the right-hand side in Figure 3) is measured with the sample insertion slot in a patulous state. However, it is impractical to assume an open condition for this slot when the analytical model for estimating complex permittivity is computed due to the large analytical area and computational resources needed. However, the proposed method does not require computation for the region outside the aperture plane as explained below. Electromagnetic wavelengths are longer at low measurement frequencies. Therefore, electromagnetic waves are cut off because they cannot propagate into the cylindrical waveguide of a sample insertion space with a sufficiently small diameter. Accordingly, the value of electromagnetic waves at the aperture area for liquid sample insertion (based on the propagation of a sample insertion hole excited from an SMA connector) appears very low because such waves decay exponentially with distance when the sample insertion length is above a certain value. The termination condition of the cut-off cylindrical waveguide is therefore assumed to be the perfect magnetic condition (PMC), which differs from the open condition in input impedance computation. On the assumption that the boundary condition of the sample insertion space's aperture area is the PMC, the mode-matching method [10, 11] can be applied to the analytical model shown in Figure 3 for calculation of the input admittance at the reference plane as seen from

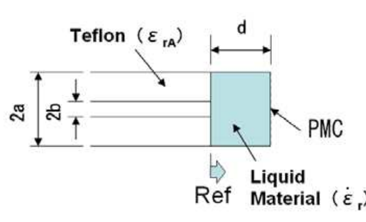

Figure 3: Analytical model.

the right-hand side using Equation (1).

$$\dot{y}_m = j \cdot \frac{2k_0 a \cdot \dot{\varepsilon}_r}{\sqrt{\varepsilon_{rA}} \cdot \ln\left(\frac{a}{b}\right)} \left(y_0 - \sum_{q=1}^{\infty} y_q \cdot x_q \right) \tag{1}$$

Here, y_m is the complex admittance (a combination of real and imaginary parts), and its inverse is the complex impedance. The complex permittivity of the inserted sample material is also uniquely decided from the measured complex permittivity. To calculate y_m, matrix elements such as y_q and x_q are first computed for convergence of the computational result with a sufficiently large q value for each change in measurement frequency.

4. FUNDAMENTAL STUDY

First, complex permittivity was estimated as an inverse problem by measuring the input impedance with tap water at a frequency of 2.49806 GHz with values of $2a = 4.1$ mm, $2b = 1.3$ mm, $d = 5.0$ mm and $\varepsilon_{rA} = 2.05$. Table 1 summarizes the means of the measurement results obtained using the proposed method along with those obtained using the TM_{010} cylindrical cavity resonator method [4] and the open-ended coaxial line method [14, 15]. In this case, the measurement jig was filled with the liquid again and the dielectric constant was measured five times each using the proposed method and the cylindrical cavity resonator method. The mean value obtained with the proposed method was $73.02 \pm 0.4 - j8.38 \pm 0.3$, which was close to the cavity resonator method result of $73.20 \pm 0.4 - j7.45 \pm 0.8$ at a frequency of 2.49806 GHz.

Room temperature was 22.4°C for input impedance measurement with the proposed method and 20.2°C for measurement with the cavity resonator method. Next, methanol, ethanol and isopropanol (IPA) samples were inserted into the jig, their input impedances were measured three times, and complex permittivity was estimated from each value. Tables 2 to 4 show the estimation results obtained with the proposed method, the measurement results obtained with the TM_{010} cylindrical cavity resonator method [4, 5], and those obtained with the open-ended coaxial line method [14, 15]. The measurement frequency value for input impedance using the proposed method is the same as that for measurement using the cavity resonator method. The outcomes show that measurement results obtained with the proposed method closely match those of the cavity resonator method.

Table 1: Measurement results for tap water.

Complex permittivity (proposed method)	Complex permittivity (Refs. [14, 15])	Complex permittivity (cavity resonator method [4])
73.55 ± 0.93 $-j8.49 \pm 0.41$	73.57 ± 0.93 $-j8.44 \pm 0.40$	73.20 ± 0.40 $-j8.28 \pm 1.50$

Table 2: Measurement results for methanol (2.5314 GHz).

Complex permittivity (proposed method)	Complex permittivity (Refs. [14] and [15])	Complex permittivity (cavity method [4])
21.33 ± 0.50 $-j13.77 \pm 0.10$	20.56 ± 0.09 $-j12.41 \pm 0.07$	22.1 ± 1.30 $-j11.4 \pm 2.10$

5. INFLUENCE OF MATERIAL FILLING SPACE DEPTH

In this study, termination was assumed to occur in the perfect magnetic condition (PMC). However, this differs from the termination condition of jigs that can be used in practice. Accordingly, input impedance variations were studied by calculating values with different sample insertion lengths when the termination condition was selected as PMC or PEC.

The results, which are detailed in reference [10], indicate little change in calculated input impedance values with insertion length variations of $d = 3$ to 5 mm. However, the calculated input impedance values shown in Figures 4 to 5 for a low measurement frequency of $f = 50$ MHz

Table 3: Measurement results for ethanol (2.5395 GHz).

Complex permittivity (proposed method)	Complex permittivity (Refs. [14] and [15])	Complex permittivity (cavity method [4])
6.26 ± 0.18 $-j7.13 \pm 0.18$	6.05 ± 0.19 $-j6.76 \pm 0.26$	6.30 ± 0.30 $-j6.80 \pm 0.30$

Table 4: Measurement results for IPA (2.5415 GHz).

Complex permittivity (proposed method)	Complex permittivity (Refs. [14] and [15])	Complex permittivity (cavity method [4])
3.04 ± 0.25 $-j3.23 \pm 0.05$	3.24 ± 0.19 $-j3.04 \pm 0.05$	3.50 ± 0.50 $-j3.00 \pm 0.10$

in relation to tap water and methanol, respectively, also indicate little change in calculated input impedance at low frequency (50 MHz) with insertion length variations of $d = 3$ to 5 mm in common with the 500 MHz and 2 GHz bands. These results can be explained by the fact that most electromagnetic waves were reflected at the discontinuity plane between the coaxial line and the cut-off waveguide because the propagation mode is the cut-off mode at the measurement frequency with the jig used here.

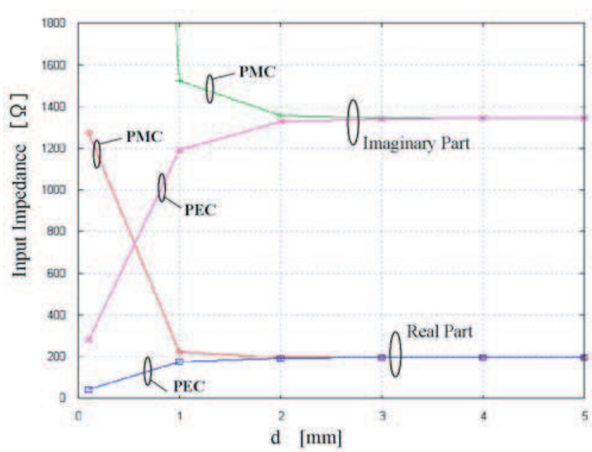

Figure 4: Results of input impedance calculation with various d-dimension values (for tap water at 50 MHz, $\varepsilon_r = 82.0 - j12.0$).

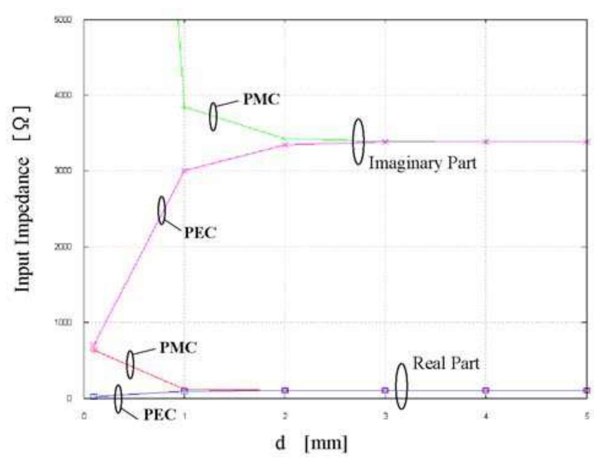

Figure 5: Results of input impedance calculation with various d-dimension values (for methanol at 50 MHz, $\varepsilon_r = 33.0 - j1.0$).

Reflected electromagnetic waves in the cut-off waveguide also attenuate within the waveguide because the inserted liquid is a high-loss material. As a result, reflected waves do not reach the reference plane. Based on these observations, it was concluded that the complex permittivity of a high-loss liquid can be estimated using the proposed method if the tip of the measurement jig is open-ended. The suitability of measurement can also be judged by checking the convergence of calculated results for input impedance with variation of the d-dimension for unknown materials.

6. FREQUENCY CHARACTERISTICS OF COMPLEX PERMITTIVITY IN CERTAIN LIQUID TYPES

The results of the study confirmed the proposed method's applicability to the measurement of complex permittivity for high-loss liquids. The complex permittivity of certain liquid types was subsequently measured under the conditions of $2a = 4.1$ mm, $2b = 1.3$ mm, $d = 5.0$ mm and $\varepsilon_{rA} = 2.0$ at frequencies ranging from 50 MHz to 3.0 GHz. The measurement results, which are shown in Figs. 6 to 9, indicate that the real and imaginary parts of the complex permittivity of tap water were 82.0 to 72.0 and 3.0 to 9.0, respectively. The corresponding figures for methanol were 34.0 to 21.0 and 1.0 to 14.0, those for ethanol (99.5) were 20.0 to 6.0 and 9.0 to 2.0, and those for

IPA were 17.0 to 3.0 and 7.0 to 3.0.

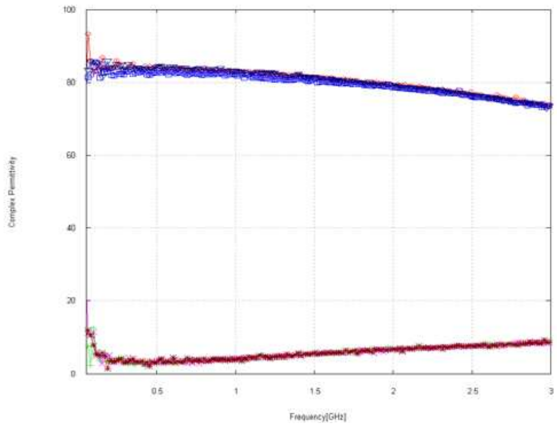

Figure 6: Frequency characteristics of complex permittivity (tap water).

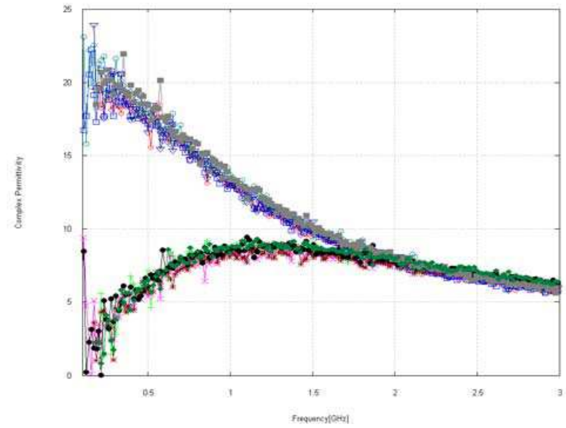

Figure 7: Frequency characteristics of complex permittivity (ethanol 99.5).

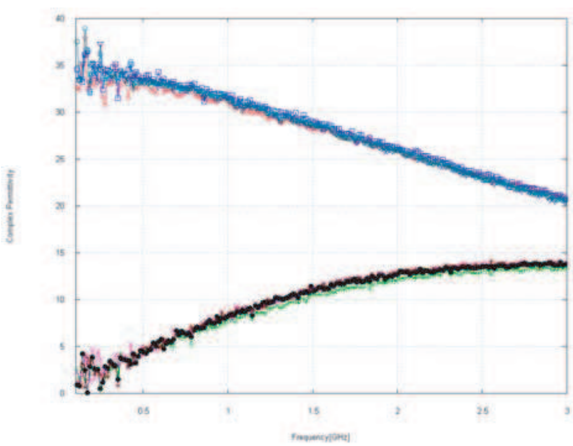

Figure 8: Frequency characteristics of complex permittivity (methanol).

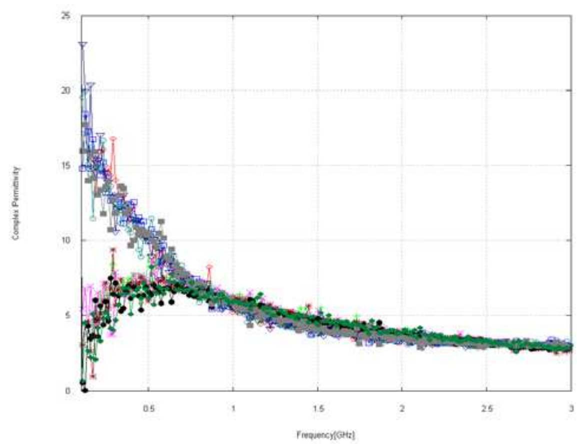

Figure 9: Frequency characteristics of complex permittivity (IPA).

The results highlighted the frequency characteristics of complex permittivity with different liquids. However, as input impedance was found to be mostly open in the ultra-low frequency band, it can be inferred that measurement precision deteriorates significantly due to large variation in the results of complex permittivity estimation. Possible methods of improving measurement precision include increasing the diameter of the coaxial tube and inserting the liquid into the coaxial region of the SMA connector. These are issues for future study.

7. CONCLUSION

This study involved verification for a proposed method of broadband measurement to determine the complex permittivity of liquids using the reflection method with an open-ended cut-off waveguide as a coaxial feed. The complex permittivity of tap water, methanol, ethanol and IPA was actually estimated from the measured input impedance. Next, measurement results and outcomes obtained using the cylindrical cavity resonator method were compared to evaluate the effectiveness of the proposed technique. The extent to which different insertion lengths and the termination conditions influence measurement results was also evaluated. Based on the outcomes, the frequency characteristics of the complex permittivity of certain types of high-loss liquids were confirmed at frequencies ranging from 50 MHz to 3.0 GHz on the basis of the measurement procedure outlined above. As complex permittivity was measured with the nose section open, the effects of liquid spillage were reduced. The method is therefore considered applicable for small amounts of liquid for cost-effective measurement in a broad frequency range. In future work, the temperature dependence of these liquids will be studied using the proposed method. However, as this method is characterized by problems in the low-frequency band, jig improvement with a particular coaxial tube diameter and material insertion space is required. Highly accurate numerical analysis for the open-ended section is also needed to deal with low-loss materials. Research to extend the method to the measurement of liquids in the millimeter band is also required.

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