Liquid Material's Complex Permittivity Measurement Using a Rectangular Waveguide and a Dielectric Tube at 800 and 900MHz band

Yumi KURIYAMA†, Naoki UEDA†, Atsuhiro NISHIKATA†, Kaori FUKUNAGA‡, So-ichi WATANABE‡, and Yukio YAMANAKA‡
†Tokyo Institute of Technology
email: nisikata@cradle.titech.ac.jp
‡Communications Research Laboratory

Abstract: A new method to measure the complex permittivity of liquid materials is presented. The liquid material is put in a dielectric tube which penetrates a rectangular waveguide. A large standard waveguide for 750–1150MHz is utilized to cover the cellular-phones’ 800 and 900MHz frequencies. The tube consists of a glass tube in the middle and two stainless steel tubes at each ends joined together. The diameters of the tube is determined to optimize for the phantom liquid measurement. Measurement was performed using deionized water, liquid phantom, ethanol, and NaCl solution. The validity of measured values were shown by comparing them with reference values or those of other measurement method.

Key words Phantom liquids, complex permittivity measurement, rectangular waveguide, dielectric tube, cellular-phone frequency.

1. Introduction

The Specific Absorption Rate (SAR) in human head exposed to the EM-field from a hand-held mobile phone must not exceed the level permitted by regulation. SAR assessment in a human head using a hand-held wireless mobile device have been standardized[1]–[3]. The SAR measurement uses the phantom consists of a shell filled with tissue equivalent liquid. The target value and permissible deviation (±5%) of the complex permittivity of phantom liquid is specified by SAR measurement procedure[2]. However, the dielectric properties of phantom liquid easily changes, mainly due to the evaporation of water[4][5]. Therefore, the measurement and control of complex permittivity of phantom liquid is important.

So far we have been investigating a new method to measure the complex permittivity of liquids using a dielectric tube which penetrates a rectangular waveguide[6]–[8]. This method enables the absolute measurement of the complex permittivity with easy operation.

In this paper, we constructed the measurement system (Fig. 1) for 800 and 900MHz which are cellular-phone frequencies. Various liquids including the phantom liquid are measured by the system, and the results are compared with other values to confirm the validity.

2. Measurement System

2.1 Rectangular waveguide

The rectangular waveguide(IEC R9, 750–1150MHz) has the inner dimension of longer side $a = 247.65\text{mm}$ and the shorter side $b = 123.83\text{mm}$. Cut-off frequency is 607MHz. The total length of the waveguide is 2160mm. The structure of the waveguide section where the dielectric tube penetrates is shown in Fig. 2.

As shown in Fig. 3, the test-port cables from the VNA(vector network analyzer) are connected to waveguide-to-coaxial adapters. To reduce the influence of higher order modes, a straight waveguide of 700mm long is connected to each adapter. The reference planes of S-parameter measurement are set at the end of the waveguides(#1, #3 of Fig. 3), and are set by TRL calibration.

2.2 Dielectric tube

We aimed at precise measurement of phantom liquid. Therefore, the actual structure must be close enough to that of the analysis model shown in Fig. 4. For simplicity, the analysis model has electric walls at both ends of the dielectric tube. Therefore, the dielectric tube made of PYREX is joined to two metal tubes made of stainless steel with epoxy adhesive, as shown in Fig. 5. The portion of the tube exposed in the waveguide is PYREX, and the portion buried in the waveguide wall is stainless steel. The inner diameter is uniform and easy to wash. The liquid to be measured is put in the tube, and two metal plugs made of brass are inserted from the both ends of joined tube, so as to have the same electric boundary condition as the analysis model. Embossed copper tape was applied at the end groove of the plug both for firm electric contact and for allowing liquid to flow through the gap.
The inner and outer diameters of the tube were set to $2\rho_2 = 14$mm and $2\rho_1 = 20$mm. $\rho_2$ was determined so that the measurement error of complex permittivity due to the random error of S-parameters be minimum. The thickness $\rho_1 - \rho_2$ was determined from the viewpoint of strength of joint portion, as well as the assumption of $2\rho_1 \ll a$ being satisfied. The structures of the joint tube and the brass plugs are shown in Fig. 6 and Fig. 7, respectively.

3. Experiment

3.1 Procedure of measurement and calculation

The procedure of measurement and determination of complex permittivity is as follows:

1. After 30 minutes of heat-run of VNA, full two-port calibration (SOLT calibration) is performed at the test port cable ends.

2. TRL calibration is performed at the reference planes #1 and #3 on the waveguide.

3. Insert the waveguide section between #1 and #3 which the tube penetrates.

4. S-matrix is measured without loading the tube and with the insertion-hole being plugged with metal plugs $\rightarrow S^{\text{unloaded}}$.

5. The empty tube plugged with metal plugs is inserted in the waveguide, and the S-matrix is measured $\rightarrow S^{\text{empty}}$.

6. Grease is applied at the contact portion of lower end of the tube and the metal plug for preventing the leak of liquid. Then, the liquid is poured from the upper end and the plug is inserted calmly with confirming no air bubbles remains inside the tube. The tube is inserted in the waveguide and S-matrix is measured $\rightarrow S^{\text{filled}}$.

7. After converting the reference planes of S-matrix to #2 (plane including the central axis of
tube), the parameter \( r \) defined by the following equation is calculated.

\[
r = \frac{s_{11} + s_{22} + s_{12} + s_{21}}{2}
\]  

(1)

8. Relative complex permittivities of dielectric tube (\( \varepsilon_r^1 \)) and of liquid (\( \varepsilon_r^2 \)) are inversely calculated so that the theoretical value of \( r \) becomes equal to the measured value of \( r \). First, \( \varepsilon_r^1 \) is determined from \( r_{\text{unloaded}} \) and \( r_{\text{empty}} \).

9. Finally, \( \varepsilon_r^2 \) is determined from \( r_{\text{unloaded}} \), \( r_{\text{filled}} \) and \( \varepsilon_r^1 \).

The mathematical procedure of the above 8 and 9 is based on ref. [6].

3.2 Measurement of deionized water

Laboratory temperature was set to 24°C, and the relative complex permittivity of deionized water was measured. The relative complex permittivity of PYREX tube was almost real and constant with frequency, and measured as \( \varepsilon_r^1 = 4.5 \). Figure 8 shows the relative complex permittivity of deionized water. Reference values in Ref. [9] for 20°C and 25°C are shown for comparison. Both real and imaginary parts are in good agreement with solid line curves, which are interpolation of reference values for 24°C.

![Figure 8: Relative complex permittivity of deionized water](image)

3.3 Measurement of liquid phantom, saline and ethanol

Temperature of the laboratory was set to 21°C. Measured liquid materials are:

- phantom liquid for 900MHz (consists of sodium chloride and sucrose, SAR measurement liquid by Kanto Kagaku Corporation);
- 0.1mol/litre NaCl solution;
- ethanol(99.5).

The measured results were compared with other measurement results by coaxial open-end probe of Agilent Technologies Co. The latter measurement was done with two different frequency range settings, and measured 10 times for each frequency setting. The measurement by two methods are performed for the same liquid sample and in the same room temperature, but the measurement place and date and time differ. Measurement results are shown in Figs. 9–11. The coaxial probe results above 1GHz are seen in two groups and slightly differs with each other, which shows that the typical error like this discrepancy exists. By comparing two methods’ results, the real part \( \varepsilon'_r \) of dielectric tube method is systematically a little lower than that of coaxial probe method. As a whole, however, both real and imaginary parts are in good agreement regardless of the value of \( \varepsilon'_r \) and \( \varepsilon''_r \). At present, the main cause of discrepancy between two methods are unknown.

4. Conclusion

We have shown the measurement results of liquid materials by newly-constructed measurement system for 800 and 900MHz where the measurement demand is high. We aimed at precise measurement. For this purpose, the PYREX and the stainless steel joint tube was fabricated with high mechanical precision. The actual boundary condition was set close to that
of analysis model, so as not to be influenced by the
through hole. Various liquid materials are measured
and good agreement with reference value or with the
measured value by coaxial probe was shown.

Future works involve the down sizing of measure-
ment system, application to 1.5GHz band, and the
use of monolithic dielectric tube.

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Figure 10: Relative complex permittivity of
0.1mol/litre NaCl(N/10).

Figure 11: Relative complex permittivity of
ethanol(99.5).