Complex Permittivity Extraction of Blood Glucose at Microwave Frequency

You Chul Jeong · Hee seok Lee · Joung ho Kim

Abstract

In this paper, a coaxial sample holder is proposed with its de-embedding and parameter extraction procedure. The S-parameters were measured up to 1 GHz using network analyzer, HP8753D, and N-type connector together with the de-embedding of N-type connector. The proposed de-embedding procedure is performed to extract electrical parameters of blood glucose, which gives the permittivity of blood glucose. We also analyzed the error of extracted parameters, which are caused by instrument error and geometrical error. Using these error analyses, we reduced the error factors of extracted parameters. We extracted electrical parameters of glucose samples through these all extraction procedure and confirmed the possibility of glucose diagnosis system based on microwave system.

Key words : glucose, microwave, coaxial line, permittivity

Ⅰ. Introduction

A good knowledge of the complex permittivity of biological media is required for utilization of microwave to biological and medical applications. Blood glucose is one example. However, there are few measured data on blood glucose. So, this paper presents measurement on blood glucose at frequency from 100MHz to 1 GHz.

In this work, we designed simple coaxial sample holder and established the procedure of de-embedding and extracting parameters. The reliable technique for extracting the electrical parameters of blood glucose is presented, which includes measurement system design, de-embedding method, parameter extraction algorithm, and the error estimation of the results as well as correction of measured results. The goal of this issue is summarized as follow: extraction of useful electrical parameters of blood glucose, propose of a calibration method of connector using equivalent model, evaluation of error factors from coaxial sample holder manufactured, demonstration of the possibility of microwave application of blood glucose measurement system.

Ⅱ. Sample Holder Design and De-Embedding Procedure

Several methods for the measurement of dielectric properties have been developed, including both time- and frequency-domain methods.[1]~[3] Automatic network analyzer measurement systems have made frequency domain methods the most economical. Applications exist in the areas of biology and medicine[4], microwave heating, nondestructive testing, and remote sensing.

At the low frequency range below 100 MHz, an impedance bridge or a parallel plate capacitor can be used for dielectric measurements. In both methods, the low-frequency equivalent model for the sample can be represented by a capacitance.

Permittivity measurement methods used above 100 MHz include resonant cavities, waveguide reflections, and the transmission-line method. In the resonant cavity technique, the amount of frequency shift in the resonant mode of the cavity determines the permittivity of the sample. The disadvantage of this method is that multiple-frequency permittivity measurements require changing the dimensions of the cavity.

In the waveguide reflection method, a sample is constructed to fit the end of a rectangular, circular, or coaxial waveguide. A single frequency electromagnetic wave is launched in the waveguide, and the amount of reflection gives the dielectric properties of the sample. Since this is a one-port measurement, the dielectric constant and conductivity are extracted from one S-parameter.[5]

The method presented in this paper is a transmission-line method using a coaxial transmission line and two-port measurements. A sample of dielectric material is placed between the two conductors of the transmission line. The 2×2 scattering parameter (S-parameter) of the two-port line is measured by using network analyzer. The S-parameters of the sample should be de-embedded, from which the complex permittivity and permeability can be found correctly.

The sample holder was designed to operate at TEM mode with a characteristic impedance of 50 Ω when empty. To completely model the sample holder, both reflection and transmission measurements are required, so a two-port sample holder was designed and is shown in Fig. 1.

The measuring section of the sample holder is 15 mm coaxial line, which consist of a 15mm(=b) diameter copper tube and a

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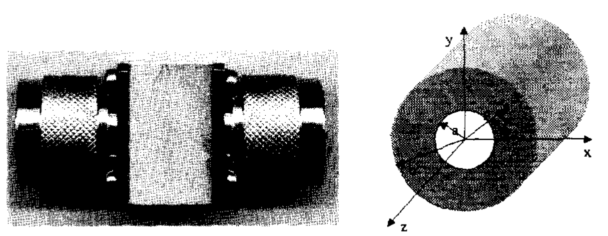


Fig. 1. Two-port coaxial sample holder for dielectric properties measurement.

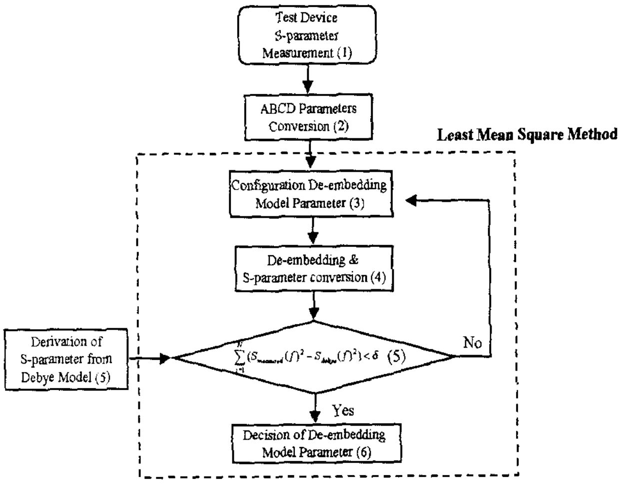


Fig. 2. De-embedding procedure for the extracting electrical parameters with no errors from the S-parameter measurements and microwave network analysis.

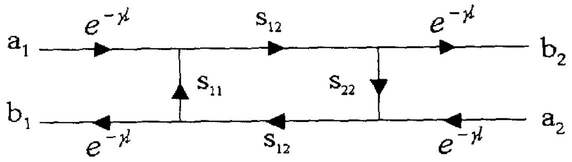


Fig. 3. Signal flow graph of the coaxial sample holder.

6mm(=a) diameter copper tube. Type N connectors were attached to the outer end of the sample holder. The restriction for this is that (b−a) be no larger than half the material wavelength at the highest operating frequency to prevent the existence of higher order propagating modes. Additionally, the desired sample length is as long as possible for low-frequency phase accuracy, but short enough to avoid resonance and to ensure adequate transmission at high frequencies.[6]

The microwave modeling and de-embedding is performed based on a microwave network analysis using S-parameters measurement and electrical parameter of pure water by the Debye model. The proposed procedure is illustrated in Fig. 2.

First, S-parameters of the coaxial sample holder are measured. From the measured S-parameters, total ABCD parameters of the test device are easily obtained. In order to adequately determine the error using the model, we made a correct model for coaxial sample holder. In this paper, N-type connector is considered as coaxial cable, where signal flow graph of S-parameter can be shown as Fig. 3.

Because both connectors are modeled as coaxial line, their S-parameter matrixes are identical. From these S-parameters, we can obtain ABCD parameter.

$$A=\frac{e^{\gamma l}+e^{-\gamma l}}{2} \qquad B=50\frac{e^{\gamma l}-e^{-\gamma l}}{2}$$
$$C=\frac{1}{50}\frac{e^{\gamma l}-e^{-\gamma l}}{2} \qquad D=\frac{e^{\gamma l}+e^{-\gamma l}}{2} \tag{1}$$

Then we must derive S-parameters of water sample from the Debye model. From these parameters, we can find model parameter.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}=\begin{bmatrix} \frac{e^{\gamma l}+e^{-\gamma l}}{2} & 50\frac{e^{\gamma l}-e^{-\gamma l}}{2} \\ \frac{1}{50}\frac{e^{\gamma l}-e^{-\gamma l}}{2} & \frac{e^{\gamma l}+e^{-\gamma l}}{2} \end{bmatrix}^{-1}\begin{bmatrix} A_m & B_m \\ C_m & D_m \end{bmatrix}\begin{bmatrix} \frac{e^{\gamma l}+e^{-\gamma l}}{2} & 50\frac{e^{\gamma l}-e^{-\gamma l}}{2} \\ \frac{1}{50}\frac{e^{\gamma l}-e^{-\gamma l}}{2} & \frac{e^{\gamma l}+e^{-\gamma l}}{2} \end{bmatrix} \tag{2}$$

In the above cascade formulation, the left side of ABCD parameters is de-embedded results, and right ones are measured ABCD parameters.

Ⅲ. Parameter Extraction and Results

The determination of the electrical parameters from the S parameters is described in the following. The measurement sample forms the dielectric medium of a coaxial transmission line.

Of the Signal E_i incident on the sample as shown in Fig. 4, ΓE_i is reflected, and $(1+\Gamma)E_i$ is transmitted. At the reference plane L, the incident signal is $P(1+\Gamma)E_i$, of which $-\Gamma$ is reflected and $[1+(-\Gamma)]$ is transmitted. The multiple reflections occurred at the interfaces 0 and L can be summed to determine the net reflection and transmission through the sample.

Rau and Wharton[7] showed that the complex permittivity of the sample can be derived in terms of the scattering parameters

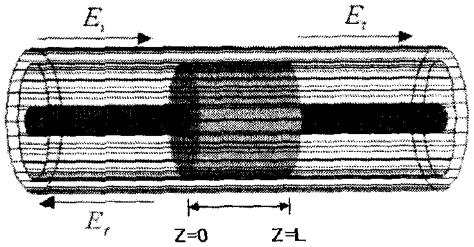


Fig. 4. Measurement setup for determining electrical parameters from S parameters.

of the coaxial section in which it is placed, yielding:

$$\varepsilon_r' = \frac{1}{j\omega\sqrt{\mu_0\varepsilon_0}}\mathrm{Im}\left[\left(\frac{1-\Gamma}{1+\Gamma}\right)\frac{1}{L}\ln\left(\frac{1}{P}\right)\right],$$
$$\varepsilon_r'' = \frac{1}{j\omega\sqrt{\mu_0\varepsilon_0}}\mathrm{Re}\left[\left(\frac{1-\Gamma}{1+\Gamma}\right)\frac{1}{L}\ln\left(\frac{1}{P}\right)\right] \tag{3}$$

Utilizing these equations given in (3), the S-parameter of distilled water from the Debye model with the de-embedding procedure gives the characteristic of the connector. We modeled N type connector as coaxial cable so two unknown variables α, β exist.

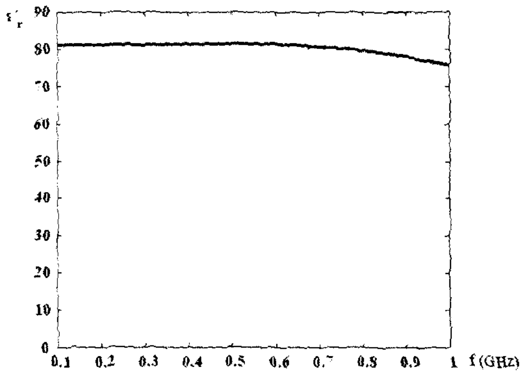
From comparing theoretical dielectric constant with measured dielectric constant of distilled water, we obtained,

$$\gamma l = \alpha l + j\beta l = 0.002 + j0.024 \tag{4}$$

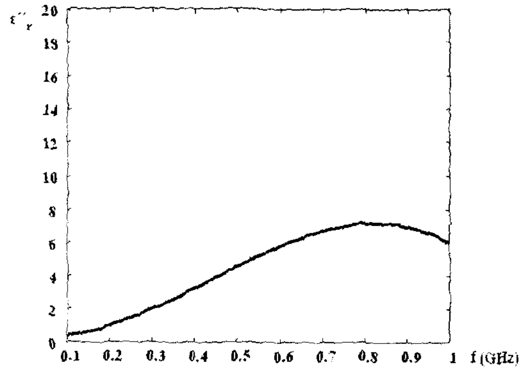
(l : effective length of connector)

So, S-parameter of N type connector is determined as,

$$[S] = \begin{bmatrix} 0 & e^{-0.002-j0.024} \\ e^{-0.002-j0.024} & 0 \end{bmatrix} \tag{5}$$



(a) Real part



(b) Imaginary part

Fig. 5. Relative permittivity of distilled water extracted from de-embedded data.

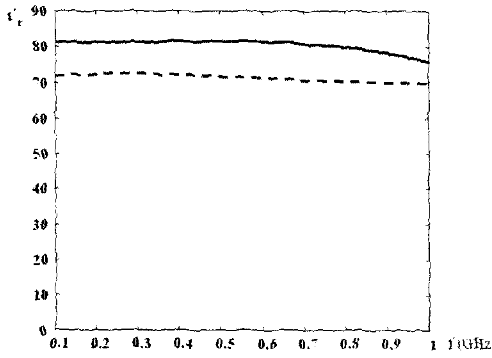
Table 1. The contents of glucose sample.

Sample No.	1	2	3	4	5	6	7	8
Concentration of glucose (mg/dL)	0	50	100	150	200	250	500	50%

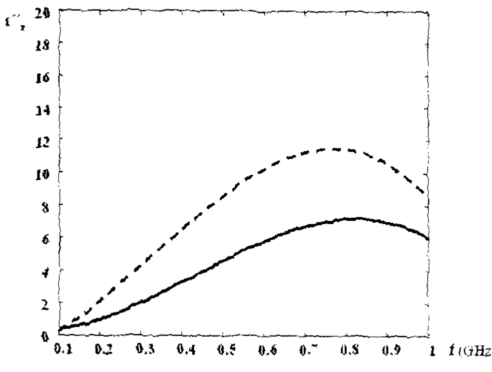
After de-embedding procedure, extracted parameters from de-embedded data have some errors. These errors are caused by instrument error and geometrical error. These errors are analyzed in chapter IV, and next figures show the results which errors are removed. Complex permittivity of de-embedded water sample is shown in next figure.

In Fig. 5, both graphs show error at above 800 MHz. This is caused by resonance of sample holder and connector characteristic. But in other frequencies, results matches well with the Debye model.

Based on the reliability of the presented extraction procedure

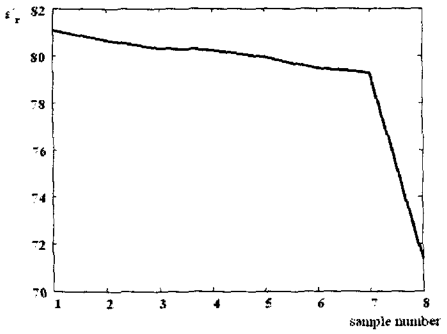


(a) Real part

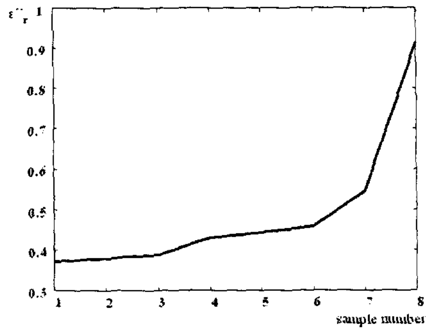


(b) Imaginary part

Fig. 6. Relative permittivity of distilled water and 50% glucose sample (solid line: distilled water, dashed line: 50 % glucose sample).



(a) Real part



(b) Imaginary part

Fig. 7. Relative permittivity of glucose samples via sample number.

at the experiment for the relative permittivity of distilled water, the electrical parameters of glucose samples were extracted by the same procedure. Glucose samples are divided into 8 classes, where sample number 1 is distilled water. The contents of each sample are shown below.

In the sample set, sample number 8 is 50 % glucose sample. Since sample 8 is saturated glucose solution, it can be considered as extreme case of glucose samples. Next figures show relative permittivity of sample number 1 and sample number 8.

As expected from electrical characteristic of biological material, real part of relative permittivity of glucose sample decreased, and imaginary part increased, as frequency increases. Electrical parameters of sample number 2 to 7 are also extracted, and its values are positioned between water and 50 % sample.

Relative permittivity at the 200 MHz is shown below, demonstrating the possibility of glucose measurement based on microwave system.

Ⅳ. Error Analysis

The two kinds of inaccuracy will be named 'ANA (automatic network analyzer) uncertainty' and 'Geometrical error'. The 'ANA uncertainties' are determined by a direct statistical method, based on the S-parameter uncertainties. And 'Geometrical error' is determined by FEM (finite-element method) simulation. For high dielectric constants (above 10), the 'Geometrical error' may be greater than the 'ANA uncertainty'.

4-1 ANA (Automatic Network Analyzer) Uncertainty

The uncertainty in S-parameter measurement is calculated using the reflection and transmission measurement uncertainty worksheets "Applying Error Correction to Network Analyzer Measurements" section of the HP 8753D Application Note. Each reflection and transmission S parameter has an independent magnitude and phase uncertainty associated with it, depending on the magnitude of the measured values.

After a full two-port calibration (SOLT), typical instrument uncertainties for the HP8753D are 47 dB directivity (D), 36 dB source match (M_S) and 47 dB load match (M_L), 0.019dB reflection frequency response (T_R), 0.026 dB transmission frequency response (T_T), and 100 dB Crosstalk (C), The degree of the measurement accuracy is given as [8].

$$\begin{aligned}\Delta S_{11} &= D + S_{11}^2 M_S + S_{21}S_{12}M_L + S_{11}(1-T_R)\\ \Delta S_{21} &= D + S_{11}S_{21}M_S + S_{21}^2 S_{12}M_S M_L + S_{21}S_{22}M_L + S_{21}(1-T_T)\end{aligned} \tag{6}$$

The phase uncertainty is given as

$$\Delta\Theta_{11} = \sin^{-1}\left(\frac{\Delta S_{11}}{S_{11}}\right) , \quad \Delta\Theta_{21} = \sin^{-1}\left(\frac{\Delta S_{21}}{S_{21}}\right) \tag{7}$$

From (V-1) and (V-2), the worst-case instrument error is calculated at each frequency and then the corresponding permittivity error is determined.

4-2 Geometrical Error

4-2-1 Higher Order Modes

The coaxial line can also support TE and TM waveguide modes in addition to a TEM mode. In practice, these modes are usually evanescent, and so give only reactive effect near discontinuities or sources, where they are excited. It is important in practice, however, to be aware of the cutoff frequency of the lowest order waveguide-type modes, to avoid the propagation of these modes.

Once k_c is known, the propagation constant or cutoff frequency can be determined

$$f_c = \frac{ck_c}{2\pi\sqrt{\varepsilon_r}} = \frac{2c}{2\pi(a+b)\sqrt{\varepsilon_r}} \tag{8}$$

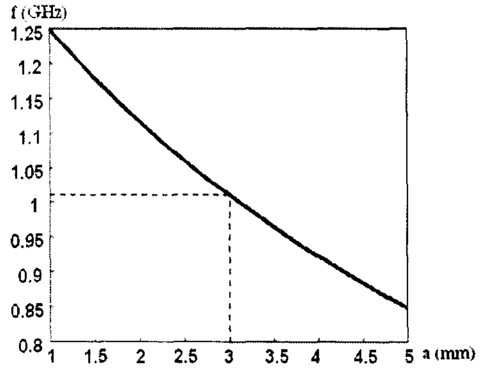


Fig. 8. Cutoff frequency of the dominant TE11 waveguide mode for a coaxial line.

In our proposed coaxial sample holder, inner conductor radius is 3 mm and its TE_{11} cutoff frequency is 1.02 GHz. So, in the presented setup, the generation of the higher modes can be avoided. But, because we extract electrical parameter at the frequency range from 100 MHz to 1 GHz, some TE_{11} mode can exist at the high frequency. These higher modes give some errors to our extracted dielectric constant.

4-2-2 Error from Parameter Extraction Equation

In the Chapter Ⅲ, we have shown relationship between electrical parameter and S-parameter. In that derivation, we assumed that outer conductor radius and inner conductor radius is designed to have 50 Ω in the air. So we used next equation

$$Z_d = \frac{1+\Gamma}{1-\Gamma} = \sqrt{\frac{\mu_r^*}{\varepsilon_r^*}} \tag{9}$$

However, if inner conductor or outer conductor radius don't exactly match designed value, above equation is not valid no longer. In that case, reflection coefficient is given by (V-10).

$$\Gamma = \frac{Z_d' - Z_0}{Z_d' + Z_0} = \frac{\sqrt{\frac{\mu^*}{\varepsilon^*}}\frac{\ln b'/a'}{2\pi} - \sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{\ln b/a}{2\pi}}{\sqrt{\frac{\mu^*}{\varepsilon^*}}\frac{\ln b'/a'}{2\pi} + \sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{\ln b/a}{2\pi}} = \frac{\sqrt{\frac{\mu_r^*}{\varepsilon_r^*}}\frac{\ln b'/a'}{\ln b/a} - 1}{\sqrt{\frac{\mu_r^*}{\varepsilon_r^*}}\frac{\ln b'/a'}{\ln b/a} + 1} \tag{10}$$

Therefore, characteristic impedance is

$$Z_d = \frac{1+\Gamma}{1-\Gamma} = \sqrt{\frac{\mu_r^*}{\varepsilon_r^*}\frac{\ln b'/a'}{\ln b/a}} \tag{11}$$

and from this equation, complex permittivity is given by (12).

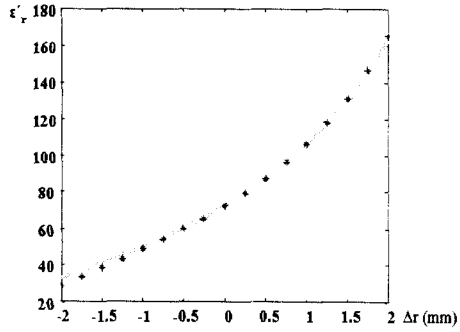
$$\begin{aligned} \varepsilon_r' &= \frac{1}{j\omega\sqrt{\mu_0\varepsilon_0}} \mathrm{Im}\left[\left(\frac{1-\Gamma}{1+\Gamma}\right)\frac{1}{L}\ln\left(\frac{1}{P}\right)\right]\frac{\ln b'/a'}{\ln b/a} \\ \varepsilon_r'' &= \frac{1}{j\omega\sqrt{\mu_0\varepsilon_0}} \mathrm{Re}\left[\left(\frac{1-\Gamma}{1+\Gamma}\right)\frac{1}{L}\ln\left(\frac{1}{P}\right)\right]\frac{\ln b'/a'}{\ln b/a} \end{aligned} \tag{12}$$

From modified equation, any change of inner conductor radius can give wrong dielectric constant. While the variation of inner conductor radius comes from machining error or thermal expansion, only machining error is considered in this paper.

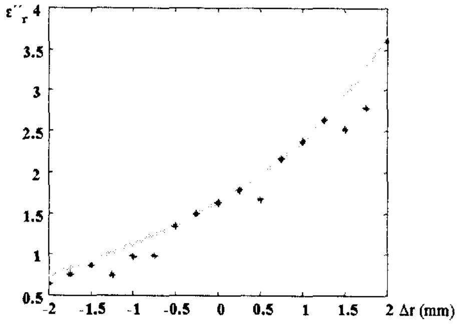
The FEM simulation was performed, when outer conductor radius, b, is 7.5 mm and inner conductor radius, a, is changed from 1 mm to 5 mm. Using these simulated S-parameters, we extracted electrical parameters of distilled water.

The relative permittivity variation of distilled water caused by inner conductor variation is given in Fig. 9, which shows permittivity at 200 MHz. It is simulated result with FEM method and calculation results with modified parameter extraction equation. Simulation result is dotted line and calculation result is solid line.

As can be seen from Fig. 9, simulation results and calculation results match well. While, considering higher mode generation in the previous chapter, cutoff frequency of higher mode is



(a) Real part



(b) Imaginary part

Fig. 9. Relative permittivity variation of Distilled water via inner conductor radius variation at 200 MHz.

decreased by incensement of inner conductor radius, the effect of higher mode is not observed in the simulation results.

V. Conclusion

In summary, the de-embedding and parameter extraction procedure is proposed with the design of coaxial sample holder. After the S-parameters were measured up to 1GHz using network analyzer, HP8753D, and N-type connector, the de-embedding of N-type connector was performed.

The proposed de-embedding procedure is applied to extract electrical parameter of blood glucose. As a result, permittivity of blood glucose is extracted. We also evaluated the errors of extracted parameters, which come from instrument error, geometrical error, and temperature variation. Using these error analyses, we reduce the errors of extracted parameter.

We have extracted electrical parameters of glucose samples through these all extraction procedure, confirming the possibility of glucose measurement system based on microwave system.

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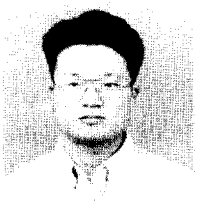

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