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Electric Parameter Extractions Using a Broadband Technique from Coaxial Line Discontinuities

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Abstract:
We have proposed a simple technique for extracting high frequency material complex relative permittivity from 0.1 GHz up to beyond 5.1 GHz despite the test fixture's discontinuities along with the characteristic impedance. The frequency range limitation depends on the test fixture's sizes. Based on the S-parameter measurements, the overall technique associates the test fixture in which the sample to characterize is inserted and the technique for altering the propagation constant of the considered region. Mathematics concepts, through their formulations, allow extracting material complex relative permittivity. The technique foundation is primarily based on the fixture calibration when there is a filling up of vacuum. A coaxial test cell is used to validate the extraction procedure. That fixture is suitable for measuring material electric parameters used in medical and civil engineering, telecommunications, and oil and gas domains. We have presented results ensuing from measures of spring water and biological materials: human tissue and liquid 900 MHz. Both biological materials are liquids and react as a muscle subjected to an electromagnetic wave. The technique is broadband, making it easy to fill up the test cell with the sample to be tested.

Keywords: Complex permittivity, discontinuity, liquid measurement, transmission-line.

1. Introduction

Electromagnetic material characterization is the radiofrequency and microwave electronics element that relates to the analysis and interpretation of material behavior following electromagnetic excitation. All methods, along with their techniques, are based on two main principles: the entrapment of a material under test (MUT) in an environment called testing cell and the S-parameter measurements [1]–[7]. One of those techniques is the transmission line, which can be used in reflection and/or transmission [8]. In this paper, we have developed that technique (despite the fixture discontinuities) [9] to extract the complex relative permittivity ε_r^* of some liquid materials in the frequency range 0.1 – 5.1 GHz with accuracy better than 5%. Many scientists have been developing techniques to sort out the discontinuity problems when computing data of intrinsic material parameters that generate order modes spreading inside of the test cell [10]–[11]. The developed technique in this paper is focused on the determination of the propagation constant γ, which is the best way to reduce the discontinuities' impacts [12]–[14]. The technique description is divided into two main parts: the mathematical formulation and the experimental validation with a second principle to counter difficulties of extracting sample losses. Experimental measurements, using some biological materials (900MHz liquid and human tissue) and normal water, have been done to validate the technique's procedure. We used a brass circular coaxial transmission line, in which the sample under test (SUT) is trapped. Also, O-rings have been set up in the fixture's design in order to avoid liquid spreading out.

2. Theory and Mathematic Model

2.1 Propagation constant

The extraction of intrinsic electric parameters is quite often based on the use of the propagation constant γ [11]-[14] when assuming that the MUT is none magnetic. This is due to discontinuities related to the transition interfaces, which are located between the input source and the ideal transmission line. This transmission-line secondary parameter is measured from S-parameters via the wave cascade matrix (WCM), written as [**C**] and given by:

$$[C]=\frac{1}{S_{21}}\begin{bmatrix}1 & -S_{22}\\ S_{11} & -\det(S)\end{bmatrix} \tag{1}$$

However, this matrix can be defined according to the transmission line propagation constant γ on the assumption that $S_{11}=0$ and $S_{22}=0$ as:

$$[C_{l_1}]=\begin{bmatrix}e^{\gamma_1 l_1} & 0\\ 0 & e^{-\gamma_1 l_1}\end{bmatrix}=\begin{bmatrix}\lambda & 0\\ 0 & \frac{1}{\lambda}\end{bmatrix} \tag{2}$$

where l is the line's length. Consider the fixture's schema as showed in figure 1, the discontinuity inverse transfer matrix is:

$$[C_\Gamma]=\frac{1}{(1-\Gamma)}\begin{bmatrix}1 & \Gamma\\ \Gamma & 1\end{bmatrix} \tag{3}$$

where

$$\Gamma=\frac{Z_c-Z_0}{Z_c+Z_0} \tag{4}$$

The total wave amplitude matrix for the device in figure 1 is written as:

$$[C_{Tot}]=\begin{bmatrix}e^{\gamma_0 l_0} & 0\\ 0 & e^{-\gamma_0 l_0}\end{bmatrix}[C_\Gamma]\begin{bmatrix}e^{\gamma_1 l_1} & 0\\ 0 & e^{-\gamma_1 l_1}\end{bmatrix}[C_\Gamma]^{-1}\begin{bmatrix}e^{\gamma_0 l_0} & 0\\ 0 & e^{-\gamma_0 l_0}\end{bmatrix}$$

which gives

$$[C_{Tot}]=\frac{1}{(1-\Gamma^2)e^{\gamma_1 l_1}}\begin{bmatrix}(e^{2\gamma_1 l_1}-\Gamma^2)e^{2\gamma_0 l_0} & \Gamma(1-e^{2\gamma_1 l_1})\\ -\Gamma(1-e^{2\gamma_1 l_1}) & (1-\Gamma^2 e^{2\gamma_1 l_1})e^{-2\gamma_0 l_0}\end{bmatrix}$$
(5)

Once the de-embedding is done, equation (5) is reduced to:

$$[C_R]=\frac{1}{(1-\Gamma^2)e^{\gamma_1 l_1}}\begin{bmatrix}(e^{2\gamma_1 l_1}-\Gamma^2) & \Gamma(1-e^{2\gamma_1 l_1})\\ -\Gamma(1-e^{2\gamma_1 l_1}) & (1-\Gamma^2 e^{2\gamma_1 l_1})\end{bmatrix} \tag{6}$$

From equation (4), the characteristic impedance of the cell test is given as:

$$Z_c=Z_0\left(\frac{1+\Gamma}{1-\Gamma}\right) \tag{7}$$

Figure 1 is the summary of the entire testing cell when the sample under test (SUT) is inside or not.

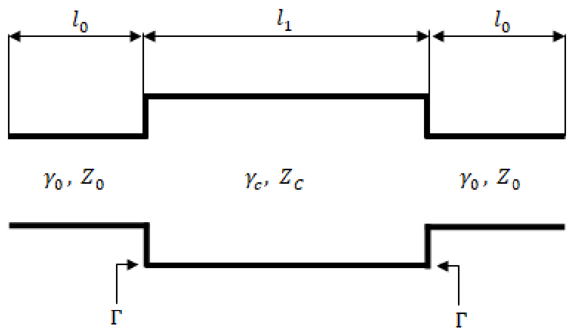

Figure 1: Simplified representation of a transmission-line in the presence of discontinuities.

The wave cascade matrix of the ideal line is given by the following equation:

$$[C_{l_1}]=[C_\Gamma]^{-1}[C_R][C_\Gamma] \tag{8}$$

Solving equation (8) leads to:

$$[C_{l_1}]=\frac{1}{1-\Gamma^2}\begin{bmatrix}\{C_{11}+\Gamma C_{12}-\Gamma(C_{21}+\Gamma C_{22})\} & B\\ \Gamma C_{22}+C_{21}-\Gamma(C_{11}+\Gamma C_{12}) & D\end{bmatrix} \tag{9}$$

$$B=\{\Gamma C_{11}+C_{12}-\Gamma(C_{22}+\Gamma C_{21})\}$$

$$D=\{C_{22}+\Gamma C_{21}-\Gamma(C_{12}+\Gamma C_{11})\}$$

Using equation (2), by identification, we need to solve the second-order polynomial, which is:

$$C_{21}\Gamma^2+(C_{22}-C_{11})\Gamma-C_{12}=0$$

We get easily the reflection coefficient at the line-connector interface. It is given as:

$$\Gamma_{1,2}=\frac{(C_{11}-C_{22})\mp\sqrt{(C_{11}-C_{22})^2+4C_{12}C_{21}}}{2C_{21}}$$
(10)

This last result is used for determining the characteristic impedance expressed in equation (4). From equation (10), combined with (2), we obtain the propagation constant expression as:

$$\gamma_1 l_1 = \ln\left\{\frac{C_{11} + \Gamma C_{12} - \Gamma(C_{21} + \Gamma C_{22})}{1-\Gamma^2}\right\} \tag{11}$$

As far as we have considered the fixture as the ideal one, it is necessary that $\Gamma_{v,m} = 0$. In that case, the propagation constant in two situations (vacuum and SUT) becomes:

$$(\gamma_1 l_1)_{v,m} = \ln\{(C_{11})_{v,m}\} \tag{12}$$

We ultimately rewrote the propagation constant in both situations: in or out of presence of the sample under test, indicated by v for vacuum and m for material under test. The phase constant in the case of vacuum is determined by $(\beta l)_v = \mathrm{Im}(\ln\{(C_{11})_v\})$ while $(\beta l)_m = \mathrm{Im}(\ln\{(C_{11})_m\})$. This constant is obtained after having disrupted the environment of the testing cell. Moreover, the energy conservation equation is often used in telecommunication as:

$$R + T = 1 \tag{13}$$

It allows settling up loss problems by considering a general mismatched system and easily demonstrating that:

$$\left(\alpha l_{(Np)}\right)_{v,m} = \frac{\left(-\left(S_{21}^{dB}\right)_{v,m} + \left(S_{11}^{dB}\right)_{v,m} + 10\log\{H\}\right)}{20\log(e)} \tag{14}$$

where

$$H = \frac{1}{\left|(S_{11})_{v,m}\right|^2} - 1$$

In the particular case where the system is matched, equation (14) becomes:

$$\left(\alpha l_{(Np)}\right)_{v,m} = -\left(S_{21}^{dB}\right)_{v,m} \tag{15}$$

S_{11} and S_{21} are found from equation (2), as results are given below:

$$\begin{cases} (S_{11})_{v,m} = \dfrac{\left(C'_{21}\right)_{v,m}}{\left(C'_{11}\right)_{v,m}} \\[2ex] (S_{21})_{v,m} = \dfrac{1}{\left(C'_{11}\right)_{v,m}} \end{cases} \tag{16}$$

Making measurements of connections in short circuit and in open circuit, the obtained reflection parameters, respectively S_{11}^{SC} and S_{11}^{OC}, give the opportunity for extracting the characteristic impedance and the propagation constant $\gamma_0 l_0$ as:

$$Z_0 = Z_n \sqrt{\left(\frac{1+S_{11}^{SC}}{1-S_{11}^{SC}}\right) \cdot \left(\frac{1+S_{11}^{OC}}{1-S_{11}^{OC}}\right)} \tag{17}$$

$$\gamma_0 l_0 = \tanh^{-1} \sqrt{\left(\frac{1+S_{11}^{SC}}{1-S_{11}^{SC}}\right) \cdot \left(\frac{1-S_{11}^{OC}}{1+S_{11}^{OC}}\right)} \tag{18}$$

where $Z_n = 50\Omega$ is the characteristic impedance of the metering equipment.

2.2 Extraction of material electric parameters

We have extracted the material intrinsic parameters: the relative permittivity ε_r, the dielectric loss tangent $\tan\delta_d$, and/or the electric conductivity σ_e. Mathematic expressions giving the methodology of these parameters have been implemented with a compute program. This is a real stake of several scientific works and publications [7]-[12]. After having linearised the phase constant, with the assumption that the SUT is a perfect insulator, equation (19) is expressed as:

$$\begin{cases} \varepsilon_r = \left[\dfrac{(\beta l)_m}{(\beta l)_v}\right]^2 \\[2ex] \tan\delta_d = 2\left[\dfrac{(\alpha l)_m}{(\beta l)_m} - \dfrac{(\alpha l)_v}{(\beta l)_v}\right] \end{cases} \tag{19}$$

and the electric conductor:

$$\sigma_e = 2\omega\varepsilon_0 \left[\frac{(\alpha l)_m}{(\beta l)_m}\varepsilon_r - \frac{(\alpha l)_v}{(\beta l)_v}\right] \tag{20}$$

3. Experiment Results and Discussion

We calibrated the vector network analyzer in 2-port to solve all measurement system blemishes [15].

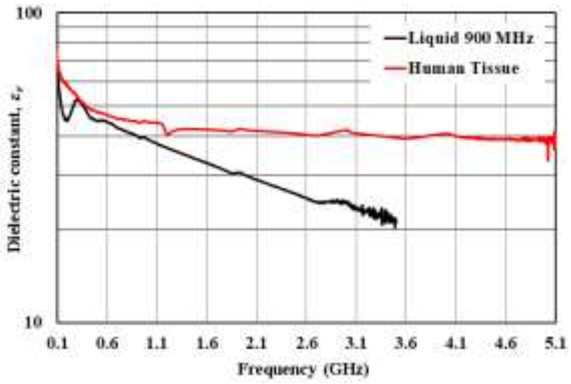

Figure 2a: Relative permittivity of human tissue and liquid 900 MHz

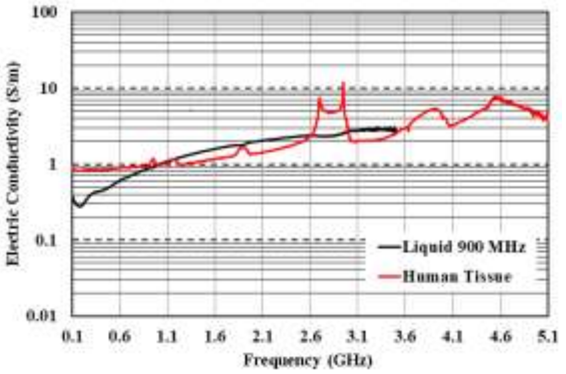

Figure 2b: Electric conductivity of human tissue and liquid 900 MHz

We compare the sound-transmission gel manufacturer values at 900 MHz to those we obtained through the following table resume.

Table 1: Benchmarking values of liquid 900 MHz

Parameters	Manufacturer	Measured
ε_r	39.3	40.03
$\sigma_e(S/m)$	0.95	0.89

We observed an error of 1.86% and 6.31% on the relative permittivity and the electric conductivity, respectively. We sketched curves to compare the human tissue electric parameters to validate the trend that has been observed with the sound-transmission gel.

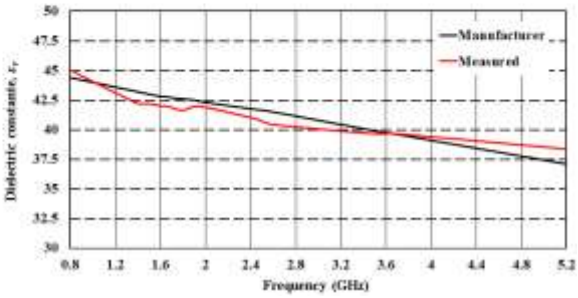

Figure 3a: Comparative results of human tissue relative permittivity

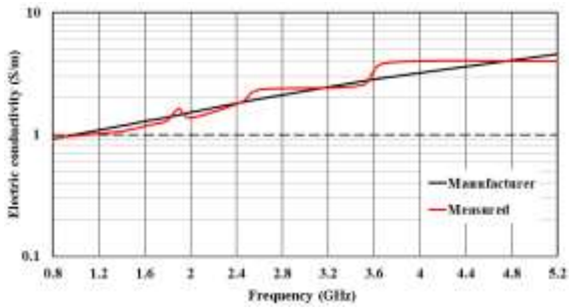

Figure 3b: Comparative results of human tissue electric conductivity of human tissue

These measured results through its sketches show a good match with the manufacturer ones.

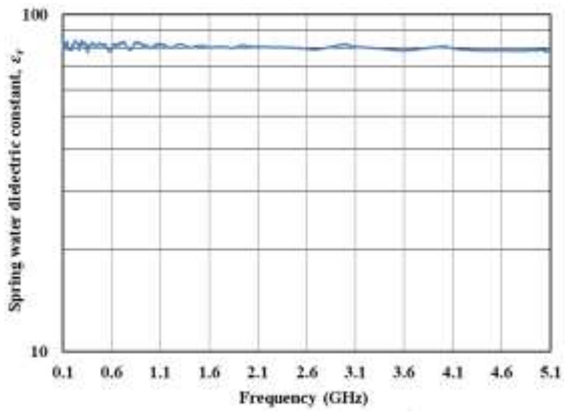

Figure 4a: Relative permittivity of spring water

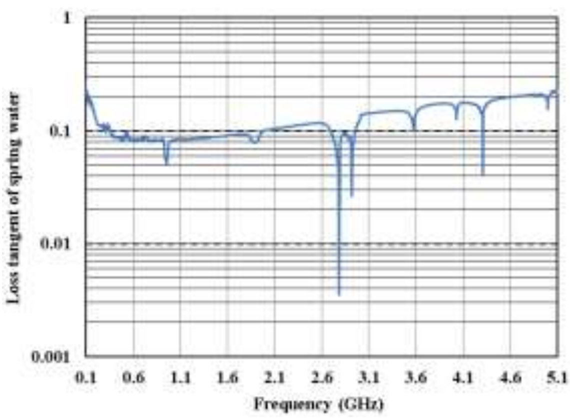

Figure 4b: Loss tangent of spring water

The spring water results are in accordance with the two transmission-line technique [16].

4. Conclusion

A broadband technique for measuring any material bulk properties (i.e. complex permittivity) has been developed. The technique utilizes a coaxial transmission-line fixture, loaded with a material in the unknown intrinsic parameters. Those parameter measurements are made despite the fixture's discontinuities, and S-parameters are computed automatically with the network analyzer in order to be used in the extraction procedure. Some measured data for standard biological dielectrics in [0.1–5.2] GHz have been presented. The technique allows for accuracy better than $\pm 5\%$ on relative permittivity and $\pm 10\%$ on the electric conductivity parameters. The sample under test conductive losses and its dielectric constant along with the device dimensions are the three reasons that caused the frequency band limitations. From different obtained results, this measurement technique should be suitable for other materials with electromagnetic applications.

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Author Profile

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