VIRTUAL TRANSMISSION LINE OF CONICAL TYPE COAXIALOPEN-ENDED PROBE FOR DIELECTRIC MEASUREMENT

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ABSTRACT

An improved virtually conical cable model of an open-ended conical-type coaxial-line probe which relate the conical coaxial line impedance to the complex permittivity of the material under test is presented. This method consists of modelling the dielectric medium by a virtual open ended transmission line of which has the same dimensions as the physical line. In the usage of conical-type open ended probe allows for easier penetration into a wide range of biological tissue types and semi-rigid materials, which is an important feature in many biological and industrial applications. The dielectric measurement technique is validated by comparing our results with experimental results on known dielectric liquids (Methanol, Butanol, and Ethanol) at radio and microwave frequencies.

Keywords: Coaxial Probe, Conical-Type, Virtual Line Model, Permittivity

I. INTRODUCTION

Measurement of dielectric properties of materials at radio and microwave frequencies has been studied for many decades in many literatures [1, 2, 3, 4]. The dielectric constant and loss factor of a homogeneous dielectric material are essential properties of dielectric materials for characterizing the interaction between an electric field and matter hence its determination is very important. There are many techniques have been developed to this issue like the Transmission/Reflection Line, Open- ended coaxial probe, Free space and resonator method (cavity method) [6, 7, 4]. The most used technique in the frequencies range of 200MHz to near 50GHz is the open-ended coaxial probe as a way of effectively and quickly characterize material properties.

The aim of this research is the study of conical type open ended coaxial line which is a coaxial line ending in a conical shape geometry. The advantage of this kind of probe is the possibility of placing the probe into the solid materials which are di cult for dielectric measurement [9, 10]. A virtual line model of the open-ended coaxial probe is used for converting the measured reflection coefficient of the contacted material into complex permittivity which is sufficiently robust to achieve precise results. The capacitive, rational, and antenna models give good results for specific frequencies.

One of suitable tools for calculating reflection coefficient may be the finite Element Method (FEM). The FEM method is well adapted to deal with this class of problems, due to its flexibility for handling complex geometries. The equations are discretized using hybrid nodal-edge elements and the results are compared with the results obtained by the results of the measurement of the electric field and the reflection coefficient of handmade probes placed in three different liquids: Methanol, Butanol and Ethanol are studied, and comparison between these results and those of which are obtained numerically.

II. BASIC EQUATIONS

Consider an open ended conical coaxial probe. This probe is assumed to be uniform along its longitudinal z axis. Maxwell curl equations for time harmonic fields are:

$$\nabla \times \boldsymbol{E} = -j\omega\mu \boldsymbol{H} \quad (1)$$

$$\nabla \times \boldsymbol{H} = -j\omega\varepsilon \boldsymbol{E} \quad (2)$$

By taking the curl of 1 and 2, the following common curl-curl equation for E is obtained:

$$\nabla \times (\nabla \times \boldsymbol{E}) - k_0^2 \varepsilon \boldsymbol{E} = 0 \quad in \;\; \Omega \quad (3)$$

where k_0 is the free-space wave number and **Ω** is the probe cross section. An appropriate boundary condition must be applied by the field vectors:

$$\mathrm{n} \times \boldsymbol{E} = \boldsymbol{0} \quad \boldsymbol{on} \quad \boldsymbol{\Gamma_1} \quad (4)$$

$$\mathrm{n} \times (\nabla \times \boldsymbol{E}) = \boldsymbol{0}\; \boldsymbol{on}\; \boldsymbol{\Gamma_2} \quad (5)$$

where $\boldsymbol{\Gamma_1}$ is electric wall and $\boldsymbol{\Gamma_2}$ is the magnetic wall. The Galerkin method is very popular finding numerical solutions to differential equations where the solution residue is minimized giving rise to the well-known weak formulation of problems. The idea is to approximate the solution to a differential equation by very simple functions. The residual associated with the PDE equation 3 is given by:

$$\partial \mathrm{F}(\boldsymbol{E}) = \boldsymbol{0} \quad (6)$$

where

$$\mathrm{R}(\boldsymbol{E}) = \frac{1}{2}\iint_{\Omega} \left(\frac{1}{\mu}(\nabla \times \boldsymbol{E}) \cdot (\nabla \times \boldsymbol{E})^{*} - k_0^2 \varepsilon\, \boldsymbol{E} \cdot \boldsymbol{E}^{*}\right) d\Omega \quad (7)$$

Suppose that E can be approximated by the expansion

$$\boldsymbol{E}(x, y, z) = \sum_{j=1}^{n} N_j^e(x, y, z) E_j^e \quad (8)$$

where $N_j^e(x; y)$ are the basis function defined over the entire domain, M denotes the number of elements in the domain, and n is the number of edge in the element, and $E_j^e$is constant coefficients to be determined. By substituting equation 8 in 7, we can obtain the generalized eigenvalue problem. More detail about this part can be fiend in [11] and [12].

Parameter	Expression	Description
r_{coax}	0.455 [mm]	Coax inner radius
R_{coax}	1.49 [mm]	Coax outer radius
L_{coax}	250 [mm]	Length of coax core into cavity
f	300 [MHz]- 3 [GHz]	Frequency
α	30	Cone Angle

Table 1: Global constant for electromagnetic model

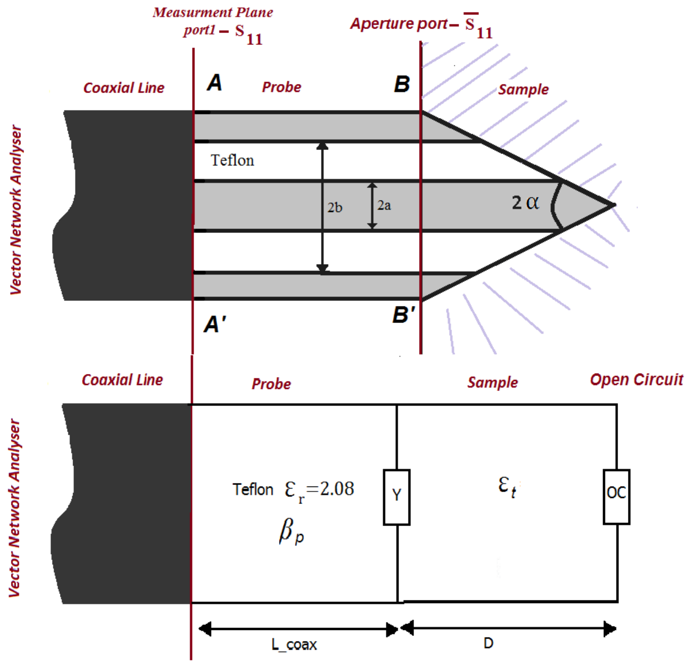

Fig 1: Improved virtual transmission-line model of open-ended conical type coaxial probe

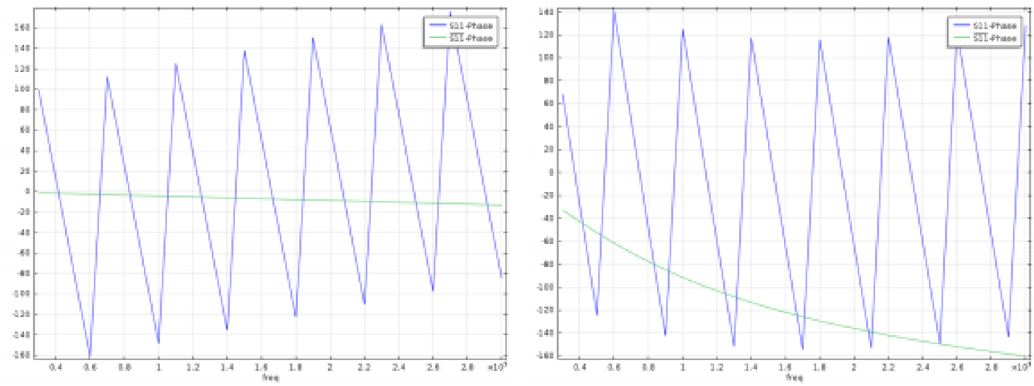

Figure 2: S_{11} and $\overline{S_{11}}$ of Air and Water by conical 30° coaxial probe

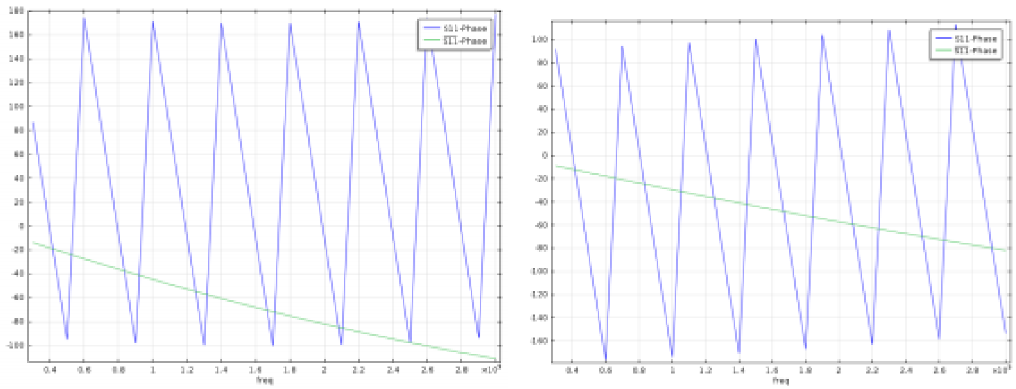

Figure 3: S_{11} and $\overline{S_{11}}$ of Methanol and Butanol conical 30° coaxial probe

To convert an electric field pattern on a port to a scalar complex number reflection coefficient we have:

$$S_{11} = \frac{\iint_{port1}(E_c - E_1)E_1^* \, ds_1}{\iint_{port1}(E_c \cdot E_1^*)ds_1} \quad (9)$$

where the computed electric field E_c on the port consists of the excitation plus the reflected field. Moreover, Modified virtual line model requires a reflection coefficient value referred at the A A0 plane, the phase difference between the B B0 and A A0 planes must be considered. The reflection coefficients relative to these two planes are related in this way

$$\bar{S}_{11} = S_{11}e^{2ikL_{coax}} \quad (10)$$

In Table 1 and Fig 1 the geometry and dimensions of structure are shown and in table 2 and Figs 4, and 3 the amplitude and the phase of reflection coefficient at measurement port (S11) and ataperture port (S11) are presented for different materials under test:

Table 2: S11 and S11 amplitude and phase for different materials

frequency=1GHz	Amp S11	Phase S11	Amp S11	Phase S11
Air	0.999	-147.954	0.999	-4.107
Water	0.898	124.132	0.898	-92.021
Methanol	0.956	171.37	0.956	-44.782
Butanol	0.975	-173.435	0.975	-29.588

These results are used for improved virtual line model of an open-ended conical-type coaxial-line probe which relate the conical coaxial line impedance to the complex permittivity of the material under test.

III. IMPROVED CONVERSION MODEL OF CONICAL PROBE

This model has studied in references [14, 13] for at coaxial probe. According to the conventional transmission-line theory the admittance at B-B' plan is given by

$$Y_{BB'} = Y_{0BB'} \frac{Y_L + jY_{0BB'} \tan(\beta_t D)}{Y_{0BB'} + jY_L \tan(\beta_t D)} \quad (11)$$

$$Y_{BB'} = jY_{0BB'} \tan(\beta_t D) \quad (12)$$

$$Y_{0BB'} = \frac{\sqrt{\varepsilon_t}}{60 \ln\left(\frac{R_{coax}}{r_{coax}}\right)} \quad (13)$$

In addition, the refereed characteristic admittance at the input of the aperture of conical probe is as follows:

$$Y_{BB'} = Y_{0AA'} \frac{1 - \Gamma_{AA'} \, e^{2j\beta_p L_{coax}}}{1 + \Gamma_{AA'} \, e^{2j\beta_p L_{coax}}} \quad (14)$$

$$Y_{0AA} = \frac{\sqrt{\varepsilon_r}}{60\ \ln\left(\frac{R_{coax}}{r_{coax}}\right)} \quad (15)$$

$$Y = Y_{0AA}\ \frac{1-\Gamma_{AA}\ e^{2j\beta_p L}\ \ coax}{1+\Gamma_{AA}\ e^{2j\beta_p L}\ \ coax} - jY_{0BB}\ \ tan(\beta_t D) \quad (16)$$

Therefore, the relation between a measured reflection coefficient and the complex permittivity can formulated into the following equations as,

$$y = \sqrt{\varepsilon_r}\frac{1-\Gamma_{AA}\ e^{2j\beta_p L}\ \ coax}{1+\Gamma_{AA}\ e^{2j\beta_p L}\ \ coax} - j\sqrt{\varepsilon_t}tan(\beta_t D) \quad (17)$$

$$Y = \frac{y}{60\ \ln\left(\frac{R_{coax}}{r_{coax}}\right)} \quad (18)$$

$$D = \frac{1}{\beta_t} tan^{-1}\left(\frac{-j}{\sqrt{\varepsilon_t}}\left(\sqrt{\varepsilon_r}\frac{1-\Gamma_{AA}\ e^{2j\beta_p L}\ \ coax}{1+\Gamma_{AA}\ e^{2j\beta_p L}\ \ coax} - y\right)\right) \quad (19)$$

$$\varepsilon_t = \left(-j\left(\sqrt{\varepsilon_r}\frac{1-\Gamma_{AA}\ e^{2j\beta_p L}\ \ coax}{1+\Gamma_{AA}\ e^{2j\beta_p L}\ \ coax} - y\right) cot(\beta_t D)\right)^2 \quad (20)$$

Two unknown parameters, y and D are estimated accurately by using two material with known properties (air and water).

IV. SIMULATION RESULTS

Figs. 5 show the two constant y and D related to virtual line part and 6 show relative permittivity and conductivity for four different materials (methanol, Butanol, and Ethanol) at 20 with conical type open ended coaxial probe. These permittivity are calculated from the reflection coefficient measured at port 1 in Figs 4 and 3. The use of such model is a good approximation for large band of permittivity at radio and microwave frequencies.

Fig 4: Handmade probes, network analyzer and connector

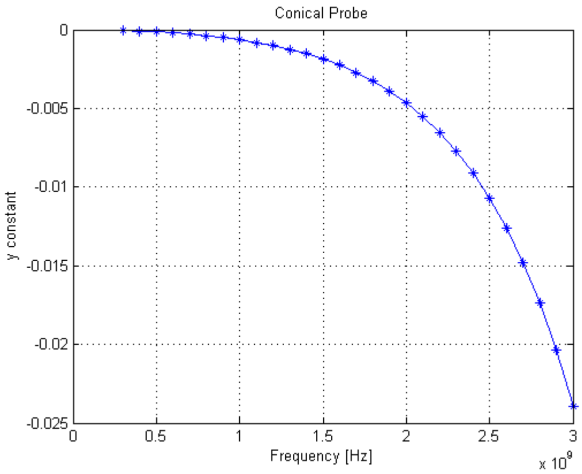

Fig 5: Virtual line model's constant (D [m], and y) for conical coaxial probe

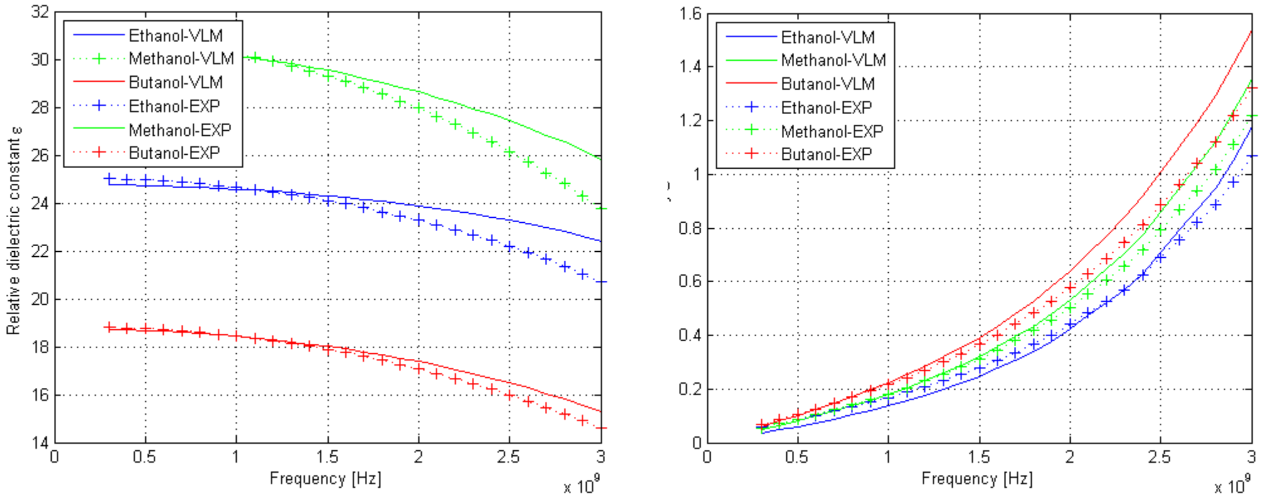

Fig 6: Complex permittivity pro les of Ethanol, Methanol and Butanol- Black lines is related to the experimental results

Fig 6 compare the simulation results obtained from a modified virtual line model with the experimental results. The results assure the validity of improved virtual line model for modelling the conical- type open-ended coaxial probe and it is accurate enough to keep its maximum discrepancy between five percent.

V. CONCLUSION

In this research, the accuracy of improved virtual line model of a conical open-ended coaxial probe was verified and reported. The complex permittivities of ethanol methanol and butanol in a wide range of frequency is calculated and compared with experimental results. The comparison shows that the virtual line model is very accurate in a wide range of frequency and using conical probe improved the accuracy and sensitivity in the low frequency range in compare to flat open ended coaxial probe. For the measurement of the reflection coefficient of liquids, it was carefully noticed that the probe should not move during the measurement, the position of the probe, should be the same for different liquids and the temperature also was kept in 25 for all the measurements; However, some part of the error is because of the measurements conditions.

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