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Measurement of Dielectric Permittivity by Conical Probe

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Measurement of Dielectric Permittivity by Conical Probe

Abstract

An open-ended coaxial line with conical tip which could be used for measurement of the complex permittivity of lossy dielectric materials will be discussed. This kind of probe has caused interesting recently. An open-ended coaxial probe with conical shape can be easily inserted into a homogeneous dielectric material (semi-rigid and of course for liquid) with a good contact between the probe and the dielectric material of interesting. The volume of the sample needn't to be infinite, moderate sample volume is enough. The conical probe is analyzed in two ways: by it's modelling theory and by HFSS software package. At first we will compare the reflection coefficients S₁₁ measured for water treated (pure), 1-pentanol (pure), ethanol (pure), methanol (pure) and saline water (0.23%) and those obtained by HFSS simulation. The modelling of the probe is being studied. Also we will do the analysis on the effects of the coaxial-line with conical-tip probe having different half cone angles open in air.

1. Introduction

Coaxial line reflection methods for measuring complex permittivity of dielectric materials at radio (RF) and microwave (MW) frequencies have been studied for a long time. Peoples in the basic and applied research area have an increasing interest on the knowledge of the dielectric property of materials. Numerous sample and probe configurations were supposed and studied, as illustrated in figure 1[1].

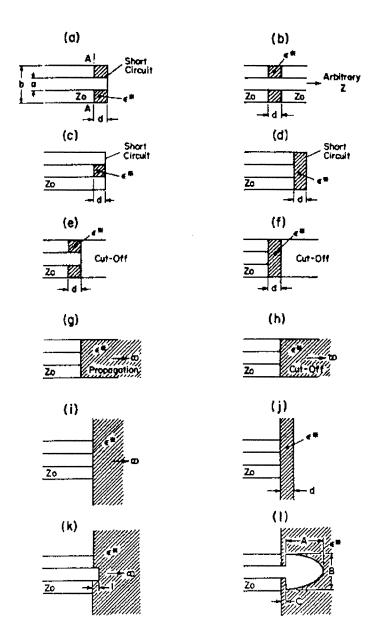


Figure 1 Various sample and probe configurations for measuring the permittivity using reflection methods[1].

In this figure, the sample may either constitute a part of the coaxial line or be placed at the end of the probe which have an outer diameter b, an inner diameter a, and the characteristic impedance Z_0 . The coaxial line operates in the TEM mode without the higher order modes. In

figure 1 (a), (c), and (d), the sample is placed at the end of the coaxial line against a short circuit. Either probe in Figure 1 (i), (k) and (l) is suitable for in-vivo measurement [1].

This research field is still an area of interest. Recently, open-ended coaxial lines filled with teflon as impedance sensors are of great interest. These are simple ended line[2-4], elliptical coaxial probes[5, 6], and conical-tip probe[7]. The elliptical -tip and conical-tip probe are shown in figure 2 and figure 3.

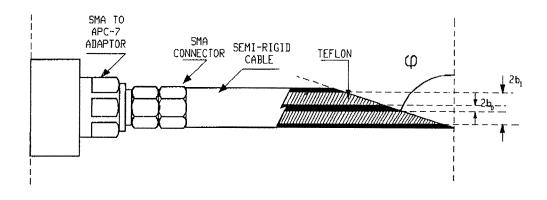


Figure 2 Open-ended elliptical coaxial probe[6].

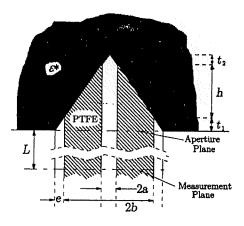


Figure 3 Open-ended conical-tip coaxial probe[7].

An open-ended coaxial probe with conical shape-cut or elliptical shape-cut can be easily inserted into a homogeneous semi-rigid material with a good contact between the probe and the dielectric material of interesting.

In the reflection methods, the complex permittivity of the dielectric materials could be obtained from the measurements of the reflection coefficients (the scattering parameter S_{11}) at a defined reference plane (usually at the interface of the dielectric materials of interest), for example plane A-A in figure 1(a). These structures in figures 1-3 are capable of operating in a wide range of frequency from 50 MHz to a few GHz. Although the resonant methods by measuring the resonant frequency and Q-factor provide excellent accuracy, they are not convenient at many frequency points[1]. It is easy for the sample preparation for the conical-tip probe, elliptical-tip probe, those in figure 1 (i), (k) and the probe in [4]. The sample tested must have so sufficiently large dimensions that the magnitude of the field on the far side can be considered negligible[4].

The obtained complex reflection coefficient is related to the complex dielectric permittivity through several models of the probe. After a comparison between various models, the virtual line model is considered to be more suitable for such permittivity measurements[8].

The object of this task is to analyze the open-ended coaxial line sensor with conical-tip

for measurement of the complex permittivity of dielectric materials, and to develop a modelling for the conical probe and a precise on-line measurement system over a wide range of microwave frequencies.

This task is composed of several steps as follow:

First, evaluating the scattering parameter S_{11} and analyzing the electromagnetic field behavior of the open-ended coaxial line with conical-tip by the aid of the HP 85180A software package (High-Frequency Structure Simulator). The HP 85180A High-Frequency Structure Simulator can take advantage of electric field (E) and magnetic field (H) symmetry to solve for a piece of the structure and then to mirror the results to symmetrical parts of the structure. Since structures that have geometric symmetry at least in one direction may have electric or magnetic symmetry as well[9]. The coaxial line has revolutionary symmetry around its axis.

Then supposing an equivalent circuit model by hypothesis. And verifying and modifying the model by experiment on deionized water, air, methanol and ethanol, etc., over a wide frequency range. It could be realized by the following steps:

- * Measuring the complex permittivity of water, methanol and ethanol etc. over a wide frequency range by the HP8753D Network Analyzer and HP probe to construct the calibration table about complex dielectric constant versus frequency.
- * Using the open-ended conical probe and HP8753D Network Analyzer or six-port measuring system to measure the reflection coefficients S₁₁ of water, air, methanol and ethanol. And using the supposed model to obtain their complex dielectric constant, with which to compare to the calibration chart.
- * Modifying the parameters of the model until we reach the correspondence of the experimental result. The open-ended coaxial line mentioned above, must be placed in contact with homogeneous, uniform sample.

It is intended to compare the reflection coefficients S_{11} among those obtained by measurement and simulated by HFSS software package, and simulated by the inverse theory.

Further investigation will be done to get permittivity values from measured S_{11} parameter (inverse problem). Later in this report, a comparison will be made between the measurement results and the data and graphics simulated by the HFSS software package (HP 85180A High-Frequency Structure Simulator) which uses the finite element method[9].

2. The prime description on the dielectric problem of conical probe

An open-ended conical probe having an outer diameter 2b and an inner diameter 2a, filled with a lossless homogeneous dielectric PTFE (teflon) which has a complex relative permittivity $\varepsilon_t^* = 2.08 - 0.004j$ is inserting into a tested dielectric material extending theoretically infinitely far away from the probe, as shown in figure 3, with a half cone angle θ of conical probe. The material being tested is assumed to be homogeneous, isotropic, linear and nonhomomagnetic, and infinitely large, having complex relative permittivity $\varepsilon_x^* = \varepsilon' - j\varepsilon''$. In fact the sample dimensions are not infinite, but a moderate scale must be used to make the field decay fairly rapidly in tested dielectric material away from the aperture.

The dimension of the coaxial line and the operating frequency are selected to permit the only propagating mode--the dominant TEM mode which excites the coaxial line and could be used to perform the measurement. Because of discontinuity at the aperture and a change of dielectric property, the TEM wave reflected back, and a number of higher order modes waves are excited. For the line and aperture are axially symmetrical, the higher order modes are TM_{0n} modes, and decay rapidly along the line by the limited line dimension. Both the TEM mode and higher order modes radiate into the mater measured[4]. The incident TEM mode has no angular variation fields but a magnetic field component H_{ϕ} along the azimuthal direction ϕ and an electric field component E_{ρ} along the direction ρ , which generates spherical waves with E_{ρ} , E_{θ} , and H_{ϕ} components[10]. With the absence of a flat metallic flange, the fringing fields must be considered. The field distribution near the aperture of the probe could be determined by applying the variational principles[11, 12]. However, the conical shaped boundary conditions must be matched at such a complicated shaped aperture plane.

The inverse problem for conical-tip ended coaxial line--to obtain the complex permittivity $\varepsilon_x^* = \varepsilon' - j\varepsilon''$ of the material from the measured reflection coefficients S_{11} is difficult and must be solved.

3. Measurement and HFSS simulation results

The HFSS software package is capable of simulating many closed area problems including some radiation problems with an artificial boundary condition. The conic-tip openended coaxial line probe in several dielectric materials is simulated in HFSS. These materials are: air, water treated (pure), 1-pentanol (pure), ethanol (pure), methanol (pure) and saline water (0.23%). Also, the reflection coefficients S_{11} of the conical probe in these materials are measured respectively with the HP 8753D network analyzer.

3.1 The simulation of the probe opening in air

The conical probe opening in air is simulated by HFSS in a frequency range from 1GHz to 6 GHz. The simulation results figure 4-17 are introduced below.

In figure 4 and figure 5, the physical 2D and 3D dimension of the simulated conical probe are displayed. In simulation, this conical probe is composed of the inner and outer conductor as well as a dielectric material (teflon) between them. The radius of the inner conductor a is 0.455 mm, the inner radius of outer conductor b is 1.49mm, and the outer radius of the outer conductor equals to 1.79mm. The half cone angle θ of this probe is 10.55 degree.

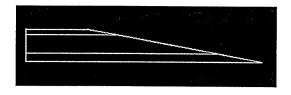


Figure 4 2D dimension of the conical probe in simulation.

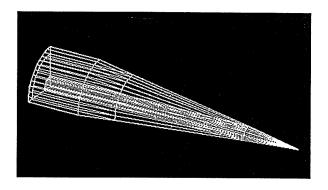


Figure 5 3D dimension of the conical probe in simulation.

In figure 6 and figure 7, we see the artificial boundary surfaces (at 3 level) to perform the simulation far away from the actual probe under consideration. Their effect is considered negligible for radiation problems if their distance from the structure is sufficiently long compared to the wavelength[9].

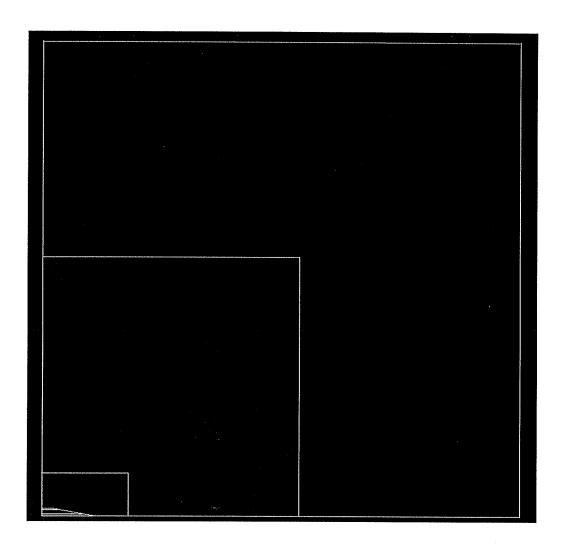


Figure 6 2D dimension of the conical probe and its boundary areas.

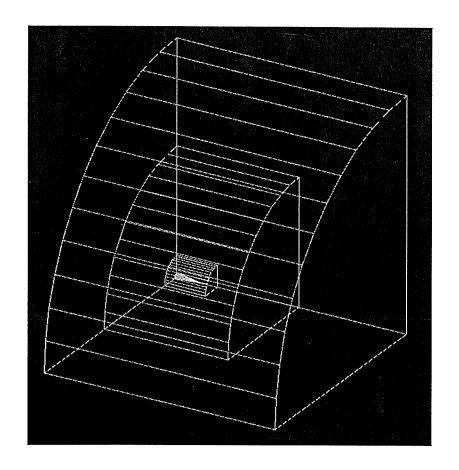


Figure 7 3D dimension of the conical probe and its boundary areas.

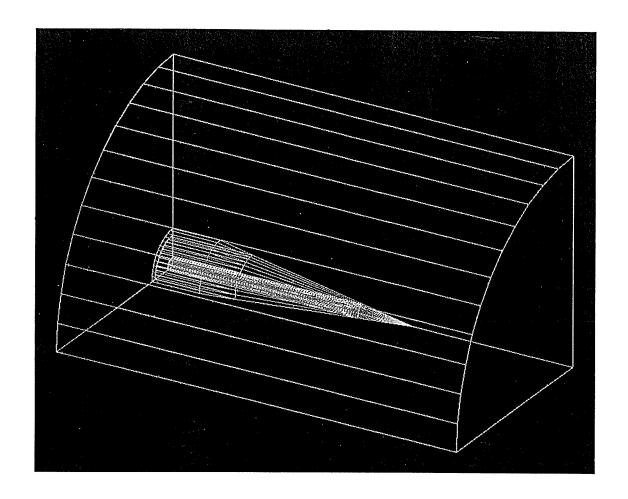


Figure 8 3D dimension of the conical probe and its innermost boundary area.

Figure 8 shows the enlarged figure 7 but only having the conical probe with the innermost boundary area--an virtual body which makes the system generate a better finite element mesh and more accurate solution for this structure[9].

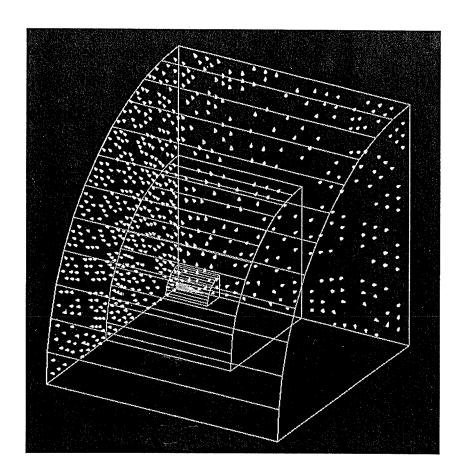


Figure 9 Plane distribution of the poynting vector \$.

Figure 9-13 show the electric and magnetic field distributions. Figure 9, 10, 11 show the poynting vector \vec{s} , electric field vector \vec{E} and magnetic field vector \vec{H} distributions on the plan x=0 and plan y=0 respectively. Figure 12 is the plot for magnitude of electric filed E, while the figure 13 for magnitude of magnetic field H.

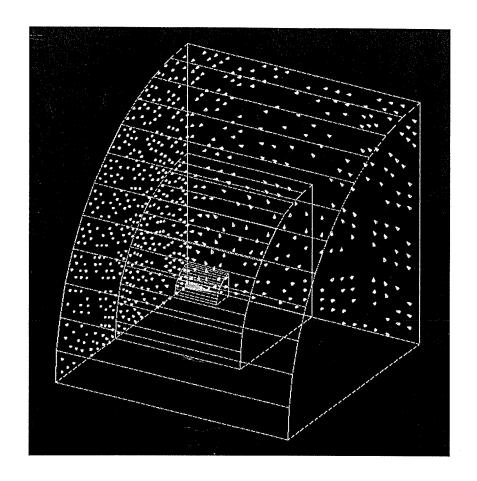


Figure 10 Plane distribution of the electric field vector $\dot{\mathbf{E}}$.

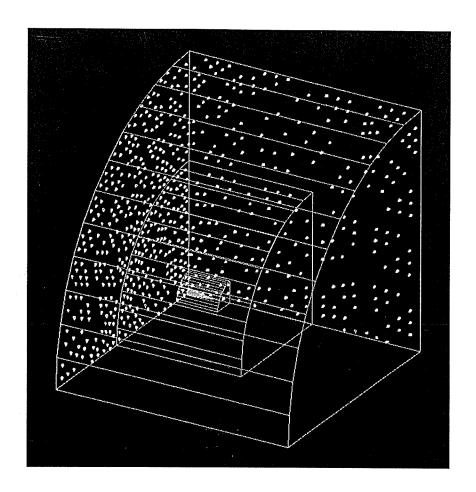


Figure 11 Plane distribution of the magnetic field vector \vec{H} .

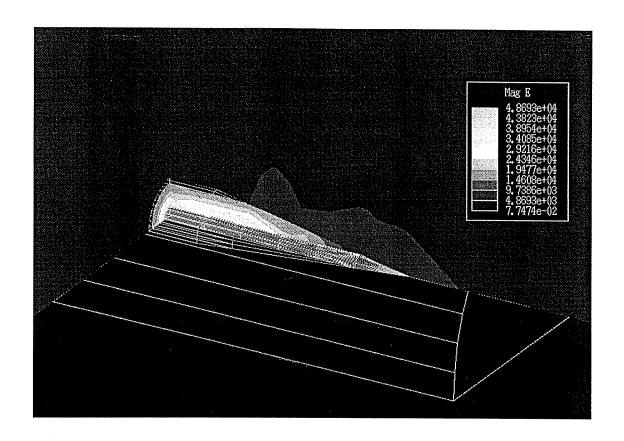


Figure 12 Plane distribution of the magnitude of electric field E.

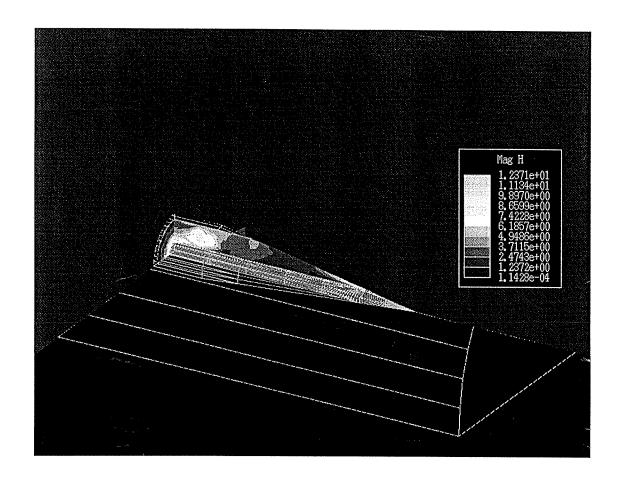


Figure 13 Plane distribution of the magnitude of magnetic field M.

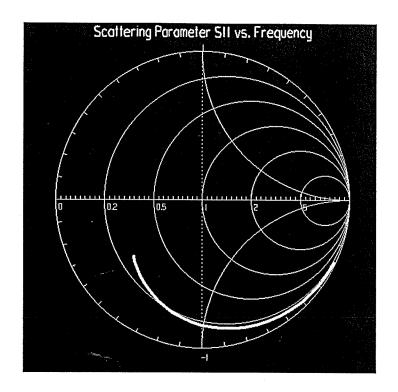


Figure 14 Smith chart for the simulated reflection coefficient S_{11}

Figure 14 is the smith chart for the simulated reflection coefficient S_{11} .

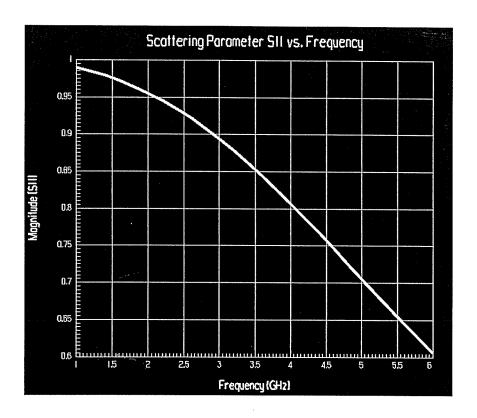


Figure 15 Cartesian plot for the magnitude of S_{11}

Figure 15-16 display the magnitude and phase of the simulated reflection coefficient S_{11} versus frequency (from 1GHz to 6GHz) respectively.

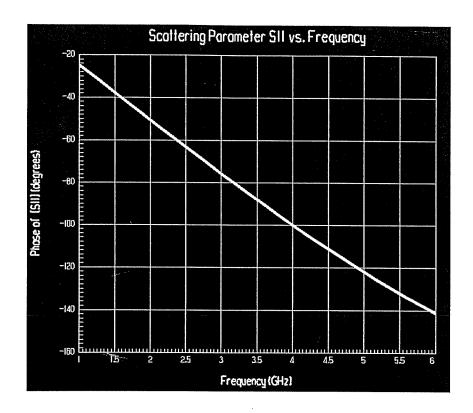


Figure 16 Cartesian plot for the phase of simulated S_{11}

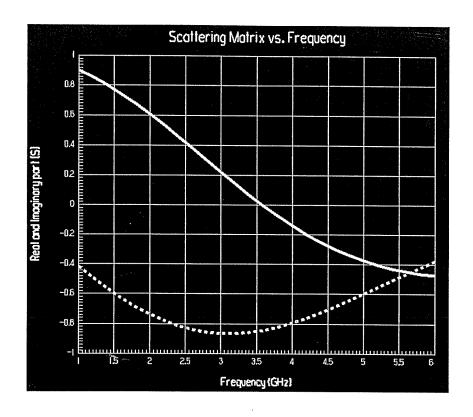


Figure 17 Cartesian plot for the magnitude of simulated S_{11}

In figure 17, the dashed line is the imaginary part of S_{11} and the solid line is the real part of S_{11} .

3.2 The measured S11 of the probe opening in air

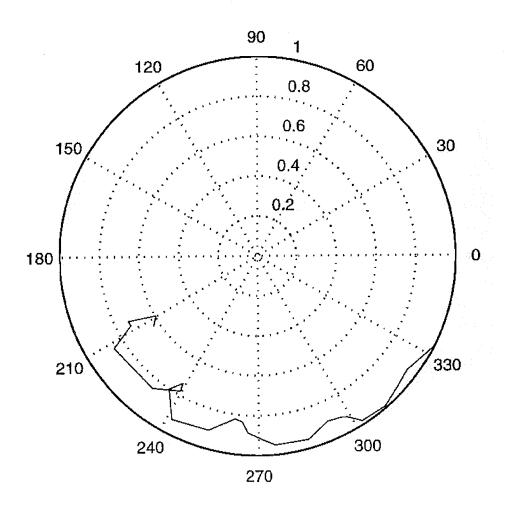


Figure 18 Smith chart for the measured magnitude of reflection coefficient S_{11}

Figure 18 is the smith chart for measured S_{11} of conical probe opening in the air.

3.3 The simulation and measurement results of the probe in other materials

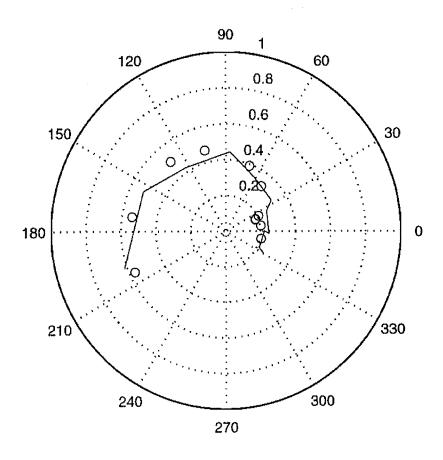


Figure 19 Smith chart for the magnitude of S_{11} for pure water.

Figure 19-23 are S_{11} on the smith charts of both the measured and simulated results for pure treated water, pure ethanol, pure 1-pentanol, saline water (0.23%), and pure methanol. In these charts, The solid lines denote the measurement results (from 1GHz to 6GHz, with step size 0.5 GHz) Circles represent the simulation results on several frequency points from 1GHz to 6GHz.

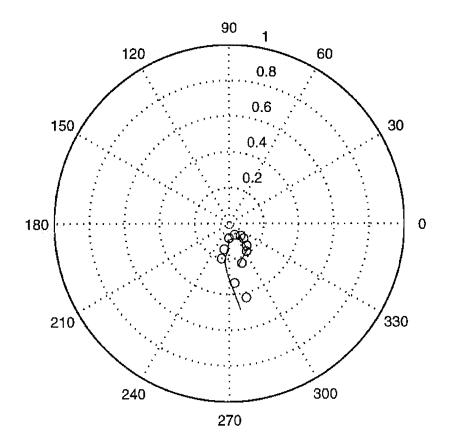


Figure 20 Smith chart for the magnitude of S_{11} for pure ethanol.

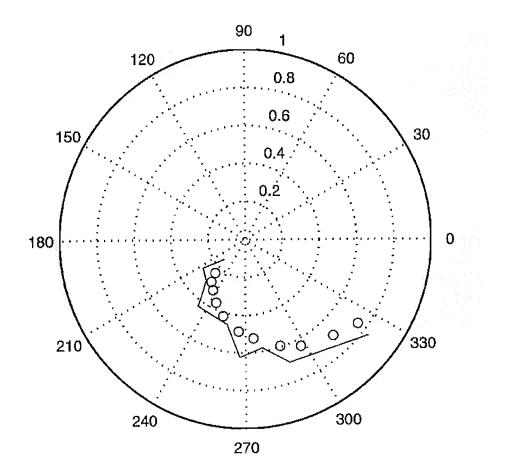


Figure 21 Smith chart for magnitude of S_{II} for pure 1-pentanol.

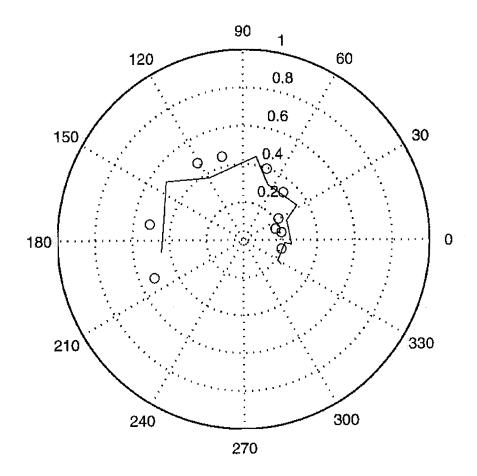


Figure 22 Smith chart for magnitude of S_{II} for saline water (0.23%).

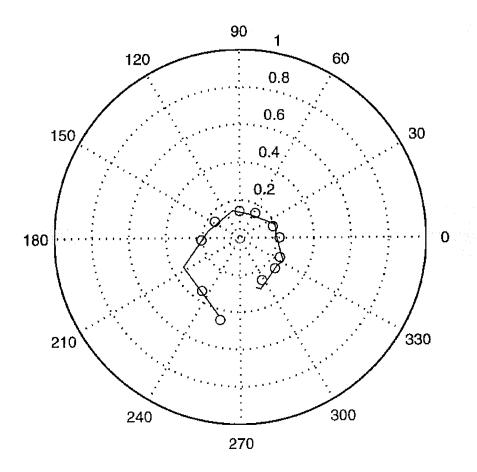


Figure 23 Smith chart for magnitude of S_{11} for pure methanol.

The measured reflection coefficients S_{11} for relevant liquids are in good agreement with the simulation.

3.4 Possible measurement system

All the measurement above is performed on the HP 8753D network analyzer with the conical probe. Another possible measurement system is shown below.

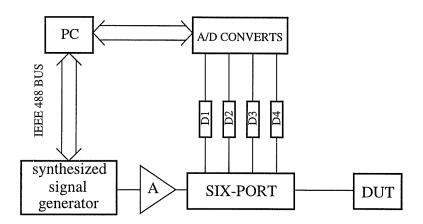


Figure 24 Six-Port on-line measurement system.

In this PC controlled measurement system, D1, D2, D3, D4 are Schottky diode detectors. The DUT (device under test) is the open ended coaxial probe with a conical-tip inserted in a test material at room temperature. A denotes the amplifier. A PC type computer takes measurements from 4 detectors of six-port reflectometer and controls the sweeping signal over the band of interest. This control is accomplished via IEEE-488 bus shared by the synthesizer. The PC also has the task to calculate the data from the four diode detectors through analogue/digital converters.

4. Conclusion

The measured and HFSS simulation reflection coefficients S_{11} for relevant dielectric liquids are shown to give good agreement, especially for pure ethanol and pure methanol.

This kind of probe is very useful to measure the permittivity, the moisture content etc. for semi-rigid materials (for example: food stuffs, gels, biological materials, muscles etc.). The portable aspect and easy-to-use characteristics of calibration for this assumed instrument may contribute to realize an interesting low cost apparatus for everyone's use.

Discussions on the theory of the modeling for the conical probe and the effects of the coaxial-line with conical-tip probe having different half cone angles opening in air will be given in a later time.

5. Acknowledgment

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