A BROADBAND COAXIAL LINE FOR ELECTRICAL CHARACTERIZATIONS OF DIELECTRICS

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ABSTRACT

Various methods have been used for the measurement of dielectric. The most common techniques are mainly based on coaxial probes, free space and reflection / transmission method by using waveguide or coaxial cell and resonance techniques. The importance of this measurement is attributed to the ability of providing the electrical or magnetic characteristics of the materials, which proved useful in multidisciplinary research. A large co-axial cell has been designed in this study to facilitate this di-electric material measurement. The cell has been calibrated to operate over a frequency range of 10 MHz to 3 GHz. The cell has been designed to be large enough to insert the sample under test inside the cell, the cell is useful for measurement of samples like Teflon or Concrete. Once the S-parameters of the two end sections are calibrated, the S-parameters of the sample region can be found, then the complex permittivity and permeability of the samples can be de-embedded using Nicolson-Ross-Weir (NRW) method. This cell is based upon coaxial transmission line principles by using coaxial cable less-loss equations, where the dimensions of inner and outer conductor diameters are computed by implying aforementioned equations. Computer Simulation Technology software has been used to simulate the dimensional design of the cell, which showed the 50 Ω characteristic impedance as required. The cell was tested and analyzed by using Teflon as a test sample material with a pre-defined permittivity of 2.08 and permeability of 1. The average of the results of permittivity and permeability of Teflon from the designed cell proved to be exactly same as the known values, for a frequency range of 10 MHz to 2 GHz.
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CHAPTER I

INTRODUCTION

1.1 Project Background

Wireless communication has been used worldwide for many years as solutions for connectivity in point-to-point and point-to-multipoint applications. The most common wireless solutions include radio frequency, television broadcast stations, mobile and cellular phones, radar and microwave systems.

Figure 1.1: An array of electromagnetic waves

Our living space is full of all kinds of electromagnetic waves, increasing in frequency. The electromagnetic (EM) spectrum contains an array of electromagnetic waves from Extremely Low Frequency and Very Low Frequency (ELF / VLF)
through Radio Frequency (RF) and Microwaves, to Infrared (IR) light, Visible Light, Ultraviolet (UV) light, X-rays, and Gamma rays, the electromagnetic waves actually have influence to the health of people [1]. As for the human body equivalent liquid, it is a very important item for all research on the absorbed EM-waves in human tissue which may be harmful for the mankind. This is a complex problem, and it involves physics and human physiology.

This project implies to understand and study the Shielding materials and its related electrical properties to protected areas such as buildings (human health) against the unknown and unwanted EM-waves, while it is easy to shield a house against the electric field generated by nearby power lines but it is much more difficult to shield against the magnetic fields they generate. The shielding effectiveness can be obtained as the sum of three contributions, absorption loss, reflection loss and multiple reflections inside the materials such as concrete wall.

Figure 1.2: Some applications of electromagnetic waves
Shielding Effectiveness Loss SE (dB) = Absorption Loss A (dB) + Reflection Loss R (dB) + Multiple Reflections Loss M (dB)

Figure 1.3: Shielding effectiveness (SE)

\[
A_{dB} = 20 \log[e^{\gamma d}]
\]
Where:
- \( A_{dB} \): Absorption Loss in dB.
- \( \gamma \): Propagation constant.
- \( d \): Thickness of wall.

\[
R_{dB} = 20 \log \left[ \frac{(Z_0 + Z)^2}{4ZZ_0} \right]
\]
Where:
- \( E_i \): Incident wave.
- \( E_r \): Reflection wave.
- \( E_t \): Transfer wave.
- \( R_{dB} \): Reflection Loss in dB.
- \( Z_0 \): Intrinsic impedance of the incident wave.
- \( Z \): Characteristic impedance of the shielding material (Wall).
M_{dB} = 20 \log \left[ 1 - \left( \frac{Z_0 - Z}{Z_0 + Z} \right)^2 e^{-\gamma d} \right]

Where:

- \( E_i \): Incident wave.
- \( E_t \): Transfer wave.
- \( Z_0 \): Intrinsin impedance of the incident wave.
- \( Z \): Characteristic impedance of the shielding material (Wall).
- \( \gamma \): Propagation constant.
- \( d \): Thickness of wall.

Figure 1.6: Multi Reflection Loss

The shielding properties of any material, to which EM waves pass through, are best described by its characteristic impedance.

\[
Z_S = \sqrt{\frac{j \omega \mu}{\sigma + j \omega \varepsilon}}
\]

\[
\gamma = \gamma_0 \sqrt{\mu \varepsilon}
\]

Where:

- \( Z_S \): The characteristic impedance of the Material
- \( \varepsilon \): Material’s permittivity \( \varepsilon_0 \varepsilon_r \) (F/M)
- \( \mu \): Material’s permeability \( \mu_0 \mu_r \) (F/M).
- \( \sigma \): Material’s conductivity \( \sigma_0 \sigma_r \) (S/M)
- \( \sigma_0, \mu_0 \), and \( \varepsilon_0 \): free space conductivity, permeability and permittivity.
- \( \gamma \): Propagation constant.
To calculate the characteristic impedance \((Z_s)\) of the concrete, all the variables have to be known before, conductivity and the permeability are known but the permittivity value is not known to assess the shielding effectiveness of the concrete, the permittivity value can be calculated depending on the S-parameters of the material under test as concrete therefore a measurement of S-parameters have to be carried out.

In this subject, the use of a Transverse Electric and Magnetic (TEM) co-axial cell in dielectric measurement (permittivity, permeability), is explained. The cell is fed at one end with a signal generator and terminated at the other end by a resistor equal to the characteristic impedance of the line, between the inner conductor (the septum) and the grounded metal exterior, an electromagnetic (EM) field propagates from the source to the termination in a fashion similar to planar fields in free space.

The exterior of the cell also forms an enclosure which both contains the internal field (that would otherwise radiate into the surroundings and perhaps interfere with peripheral equipment), and conversely, shields the internal volume from the external electromagnetic environment.

The source at the input side can be continuous wave (CW) from a network analyzer, or a pulse generator, the source and termination are connected by coaxial cables, the coaxial can support TE and TM waveguide modes in addition to a TEM mode [1].

1.2 Problem Statements

Recently, the importance of the complex dielectric properties measurement of materials at radio frequency has rapidly increased especially in the research fields, such as material science, microwave circuit design, absorber development, biological
Dielectric properties of materials are those electrical characteristics of materials that determine their interaction with electric fields.

In all microwave (RF and MW) applications electromagnetic (EM) fields interact with materials that are either solids, liquids or gases. Viewed on macroscopic scale, all materials will allow EM-fields to pass into them to some extent, even good conductors and superconductors, therefore, in one sense, all materials may be said to be dielectric. The word “dielectric” is a contraction of “dia-electric” which means that electric field can (to some extent) pass through them. In designing RF and MW components for applications, therefore, it is desired to understand just how electrical and magnetic field propagate into and through materials. We need to be able to measure the dielectric and magnetic properties of the materials.

Accurate measurement and effective shielding is built to protect areas against the unknown and unwanted EM-waves. The permittivity is important factor of the materials that can be used in the shielding effectiveness assessment, antenna substrate and the dielectric (insulator) used in capacitors. Permittivity determination depends on the scattering parameters (S-parameters) measurement of the material under test.

The scattering parameters of the material under test require appropriate measurement setup to be measured; the identification of electric and magnetic properties of the material can be achieved using various techniques as discussed in previous literature, such as: free space, resonant cavity and parallel plate cell test.

Aforementioned yester techniques, however, have their own limitations and disadvantages that make them not suitable for the accurate dielectric measurements. Their shortcomings include limitation to narrow band frequencies only, need of large and flat material under test (MUT), multiple reflections between antenna and surface of samples and diffraction effects at the edge of samples due to non-uniformity of
system [6]. TEM (Transverse Electric and Magnetic) co-axial cell can overcome most of these problems, with its well-matched coaxial-to-waveguide connector.

This structure can produce uniform TEM field between its two conductors, TEM co-axial cell can operate from very high-frequencies and for a wideband frequency range.

Here we use a new technique to provide a wideband coaxial-to-waveguide connector and then to match the TEM co-axial cell to the measuring devices for a wide frequency range, the dimensions of the optimal cell should be coherent with the real measurement needs (enough space to handle and set the under-measurement dielectric inside the cell) and on the other hand, to keep a matched impedance for the cell and also to reduce the radiation-loss.

1.3 Project Objectives

The measurable objectives are as follows:

i. To design and fabricate TEM co-axial cell operating from 10 MHz to 2 GHz and must ensure field uniformity with 50 ohm impedance.

ii. To investigate the ability of TEM co-axial cell to provide a uniform TEM mode and its feasibility to be used as standard dielectric measurement set-up.

iii. To determine the dielectric properties of any solid material at 10 MHz to 2 GHz based on the measured S-parameters of the material.
1.4 Project Scopes

The scope of this project can be clarified as follow:

i. Simulation

This project is primarily concerned with the design of TEM coaxial cell. In this research CST software is used to simulate the designed TEM coaxial cell in order to acquire a characteristic impedance of 50 Ω over a frequency range of 10 MHz to 2 GHz.

ii. Fabrication

The cell has been built using aluminum metal because aluminum is a good conductor and very light weight. The fabricated cell is low-cost and enough spacey to handle the sample inside the cell.

iii. Verification

The cell was tested and analyzed by using Teflon as a test sample material with a pre-defined permittivity of 2.08 and permeability of 1.
1.5 Expected Results

The expected results of this project are:

i. By using CST software to design coaxial cell. The expected value of characteristic impedance is 50 ohm with the values of frequency from 10 MHz at 2 GHz as shown in the Figure 3.22.

![Graph showing expected results of characteristic impedance](image)

Figure 1.7: Expected results of characteristic impedance
ii. After implementing the design coaxial test cell with MUT as Teflon. The expected permeability is (µ = 1) and permittivity is (ε = 2.08) as show in Figure 1.8 a and Figure 1.8 b.

Figure 1.8 a: Expected permeability

Figure 1.8 b: Expected permittivity
CHAPTER 2

LITERATURE REVIEW

2.1 Technology Developments

Electromagnetic pollution (or EMF pollution) is a term given to all the man-made electromagnetic fields (EMFs) of various frequencies, which fill our homes, workplaces and public spaces.

RF power in the ambient is high due to the massive use of electronic devices, broadcasting devices that used for mobile applications and other electrical equipment. Most of these electronic devices operate in concrete based constructed buildings. The materials which are used in the construction have different electrical properties.

2.1.1. Introduction

Theoretically, all materials could be used for radiation shielding if employed in a thickness sufficient to attenuate the radiation to safe limits; however, due to certain characteristics, lead and concrete are among the most commonly used materials.

The efficiency of concrete structures as a shielding material depends on its electromagnetic properties, electrical conductivity and permittivity.
Dielectric measurements have been performed at National Physical laboratory (NPL) over much of the twentieth century but work in the microwave region of the spectrum only commenced in earliest in the late 1960s. Instruments developed under that program are varied as TE_{10}-mode cavities and open resonators, remain in use today because they provide the most sensitive means of measuring very low dielectric losses in the frequency range 10 - 144 GHz [7]. Various methods have been used for the measurement of dielectric properties including both time and frequency domain methods. Economically a frequency domain method is selected due to automatic measurement systems [8].

On the other hand, non-resonant methods have relatively higher accuracy over a broad band frequency and necessitate less sample preparation compared to resonant methods, they allow the frequency- or time-domain analysis, or both, owing to their relative simplicity, broad frequency coverage, and higher accuracy, transmission–reflection method (a kind of non-resonant method) are widely utilized for characterization of materials.

The existing systems are mainly based on waveguides coaxial probes, free space, and reflection–transmission method and resonance techniques [9]. Waveguide has the advantages of high power handling capability and low loss but it require the sample to be machined out as fit as the cross section of the waveguide. Practically waveguides are not appropriate for lower frequencies due to the large size.

### 2.1.2. Resonance methods

For resonant measurements, the permittivity or permeability is determined from measurements of the resonance frequency and quality factor (Q). The quality factor is calculated from \( Q = f_0/\Delta f \), where \( f_0 \) is the resonance frequency and \( \Delta f \) is the frequency difference between 3 dB points as Figure (2.1).
Resonant measurements are the most accurate methods of obtaining permittivity and permeability. However, there are limitations on the frequencies and loss characteristics of the materials that can be measured with the method. There are many types of resonant methods available such as resonators cavities, split cylinder resonators, cavity resonators, Fabry-Perot resonators etc. This section will concentrate on the general overview of resonant measurements and the general procedure using a cavity resonator [9].

Resonant cavities are high Q structures that resonate at certain frequencies; a piece of sample material affects the centre frequency ($f$) and quality factor ($Q$) of the cavity, from these parameters, the complex permittivity ($\varepsilon_i$) or permeability ($\mu_i$) of the material can be calculated at a single frequency.

This method uses a rectangular waveguide with iris-coupled end plates, operating in TE$_{10}$ mode for a dielectric measurement the sample should be placed in a maximum
electric field and for a magnetic measurement, in a maximum magnetic field. If the sample is inserted through a hole in the middle of the waveguide length, then an odd number of half wavelengths \((n = 2k + 1)\) will bring the maximum electric field to the sample location, so that the dielectric properties of the sample can be measured. An even number of half wavelengths \((n = 2k)\) will bring the maximum magnetic field to the sample location and the magnetic properties of the sample can be measured as Figure 2.2 [10].

\[
\begin{align*}
\varepsilon'_r &= \frac{V}{2\pi f} \left( \frac{1}{f_c} - \frac{1}{f_s} \right) + 1, \\
\varepsilon''_r &= \frac{V}{4\pi f} \left( \frac{1}{Q_c} - \frac{1}{Q_s} \right)
\end{align*}
\]

\(V\) is the volume, index \(c\) is for the empty cavity, index \(s\) is for the sample loaded.

Figure 2.2: Resonates cavity measurement

Hole needs to be drilled exactly in the middle of the waveguide length and the two iris-coupled end plates need to be manufactured. The dimension of the iris hole is \(b/2.2\), where \(b\) is the narrow dimension of the waveguide cross section as Figure 2.3.
Figure 2.3: Cavity resonant parts and inserted sample

Figure 2.4 shows measurements of three different samples with this cavity, the three measurements are presented on the same graph for comparison purposes [10].

The resonant frequency of the empty cavity is $f_c = 9.9375$ GHz (for TE107 mode) and it shifts to a lower frequency when the sample is inserted in the cavity. When the resonator is loaded with a sample, the resonance curve broadens, which results in a lower quality factor $Q$. On the y-axis of Figure 2.4 is the magnitude of the linear
transmission coefficient $|S_{21}|$. The 8720ES network analyzer is used for these measurements. On the left of the figure is a calculation for the Sample 2, which has a cross section of 0.29 by 0.157 cm.

Although the resonant cavity technique is extremely accurate, it is still subject to errors. The network analyzer must have excellent frequency resolution (1 Hz) to measure very small changes in the Q factor. The sample cross-section dimensions must be known precisely. There is also additional error due to the approximation in the analysis (perturbation theory). This method has limitations for low-loss samples due to the comparatively low Q-factor of the empty rectangular waveguide cavity. A cylindrical type of cavity offers much higher Q-factors, but it has its own disadvantages, the biggest of which is the difficulty to manufacture it.

2.1.3. TE$_{10}$ mode dielectric

Initially, the dielectric resonator technique for measurements of permittivity and losses of low-loss dielectrics was introduced by Hakki – Coleman in 1960 employing the TE$_{011}$ mode of operation in a rod resonator terminated from both sides by conducting planes. Since its discovery, it has become one of the most accurate and the most frequently used techniques for measurements of permittivity and dielectric losses of solid materials. It is also known under different names as the Courtney or parallel plate holder and it is also proposed as one of International Standards IEC techniques for measurements of the complex permittivity of low-loss solids. A very simple measurement configuration and easy access for putting and removing specimens are advantages of this cell [6].
Figure 2.5: Rectangular cavity resonator

Figure 2.5 show that classic measurement set-up is usually based on rectangular $\text{TE}_{10}$ mode waveguides which becomes very large, expensive and non-practical for the lower frequencies in the MHz range.

2.2. Free space method

A pair of spot-focusing horn lens antennas have been mounted on a large table thick aluminum, for these antennas, the ratio of focal distance to diameter of the lens (F/D) is equal to one and D is approximately 30.5cm. A focal distance sample holder is mounted at the common focal plane for holding planar samples as Figure 2.6.

Figure 2.6: Measurement of sample using free space method
The transmit and receive horns have been mounted on a carriage and the distance between them can be changed with an accuracy of 0.001". The 3-dB beam width and the depth of focus for these horn lens antennas are approximately one and ten wavelengths, respectively. The antennas are tuned at 16 GHz, but they can be used over the entire bandwidth (14.5-17.5 GHz) of the circular waveguide feeding the antenna.

Diffraction effects at the edges of the sample are negligible because of spot-focusing of lens antennas, if the minimum transverse dimension of the sample is greater than three times the beam width of the antenna at the focus. This condition has been verified experimentally [5].

The focused antennas are connected to the two ports of the (HP 8510B) network analyzer by using coaxial cables, rectangular to circular waveguide adapters, and coaxial to rectangular waveguide adapters. The network analyzer is used to make precision measurements of S-parameters of the sample in free space.

The (HP 9836) computer along with the (HP 85161), A measurement automation software is used to improve the repeatability of the sample measurements and for overall automation of the measurement system.

A full 2-port calibration can be performed up to the coaxial to waveguide adapters by using a waveguide calibration kit for the measurement system shown in Figure 2.7. The measured S-parameters are different from the actual S-parameters of the sample in free space because of multiple reflections due to rectangular to circular waveguide transitions and horn lens antennas. Therefore, it is necessary to calibrate the measurement system in free-space [10].
High temperature measurements are easy to perform in free space since the sample is never touched or contacted, the sample can be heated by placing it within a furnace that has “windows” of insulation material that are transparent to microwaves.

2.3. Parallel Plate Waveguide (PPW)

A parallel-plate waveguide can be used as TEM cell wideband frequency range, to increase the efficiency of the PPW to operate up to 1GHz, the radiation losses and higher propagation modes should be controlled.

The feeding section should be matched to get minimum return loss, a novel design is pioneered to obtain good matching, and a parallel plate waveguide based on conical feeding section is designed as new wideband cell that can provide uniform e-field as Figure 2.8.
This cell has good ability to measure the electrical properties of the material from 10 MHz range up to 1GHz [6].

In the geometry of the parallel plate waveguide that Figure 2.9 shows, the strip width (W) is assumed to be much greater than separation (d), so that fringing fields and any x-axis variation can be ignored, a material with permittivity ($\varepsilon$) and permeability ($\mu$) is assumed to fill the region between the two plates.
The restriction is that the higher propagation modes limit the highest operating frequency. RF Coaxial connectors are used to connect the TEM cell to vector network analyzer. The inner conductor of the RF connector is connected to the lower plate while the outer conductor is connected to the lower plate as Figure 2.10.

![TEM cell connections to vector network analyzer](image)

Figure 2.10: TEM cell connections to vector network analyzer

A conical shape is inserted between the upper plate and the inner conductor of the RF connector. The conical shape is tapered at 60° to improve the matching and to reduce the non-uniformity of the system [6].

### 2.4. TEM coaxial test cell

This method is recommended by the American Society for Testing and Materials (ASTM) for shielding effectiveness measurement of samples of conductive coatings of composite materials and conductive loaded plastics. The advantage of this method is that the far-field testing of the sample is possible by taking the measurement in a TEM mode field inside a coaxial line. The coaxial holder is essentially an expanded section of 50-Ω circular coaxial line which may be disassembled at the centre to allow the insertion of a test sample as shown in Figure 2.11.
The shielding effectiveness of the material is obtained from the readings, one with the test sample and one without the test sample but with the reference in place [12].
The coaxial cell is a tapered coaxial transmission line, terminated by a standard 50-ohm coaxial connector at the small-diameter end. It has a straight coaxial section at the large-diameter end that accepts the material under test (MUT). The taper maintains the 50-ohm transmission-line impedance from one end to the other.

As mentioned previously, we need a large coaxial cell design. As a result, the outer conductor radius (b) is made as large as possible, while the inner conductor radius (a) is adjusted for a characteristic impedance of 50 ohm in the sample region.

The measurement device may consist of a network analyzer as shown in Figure 2.13, which is capable of measuring insertion loss and return loss. The shielding effectiveness is determined by comparing the difference in attenuation of a reference sample to the test sample, taking into account the insertion and return losses. The measurement procedure consists of two stages; in the first stage, a reference sample is placed in the test adapter to compensate for the coupling capacitance.
CHAPTER 3

METHODOLOGY

3.1. Overview

An enhanced and improved dielectric measurement device has been designed and constructed for permittivity measurement of MUT; the permittivity is measured in the frequency range 10 MHz–2GHz. The cell has to be used as TEM coaxial cell and it should be in large size, on the other hand the cell should be enough spacey to allow the immersing of material under test.

3.2. Research activities

This project has been conducted into four phases:

The first phase to design the cell depends on the geometry of the coaxial cell, the outer diameter (D) the inner diameter (d) would be used to get the characteristic impedance 50 Ω as shown in Figure 3.1, which should be matched to the characteristic impedance of the coaxial – type connector input ports network analyzer.
REFERENCES


