Design and Assessment of Cavity Perturbation Method for Dielectric Constant Measurement.

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Abstract

It has been observed that the heating due to high power delivery over Ethernet cables, affects signal transmission in the remote powered Ethernet (rpE) systems. Additionally, the thermal variation on the cables, sometimes due to extreme weather conditions, modifies the cable properties, impacting channel performance. In particular, the cable’s transmission parameters such as Return Loss, Attenuation, etc. are markedly influenced as a consequence of rapid heating and cooling cycles. However, to better understand how the cable’s transmission parameters drift, there is a need to investigate the changes in the cable primary parameters such as capacitance, resistance, conductance, etc. Then the cause of the modification, for instance, in the bulk capacitance, can then be established by investigating the permittivity of the dielectric materials.

In this study, the dielectric constants of some pure dielectric samples were examined at 2.4GHz, using the Cavity Perturbation Method of the ASTM D2520-13. The tests thermally cycled the dielectric samples from an ambient temperature of +20°C to a maximum of 70°C and calculated the dielectric constant at a temperature below 70°C and at room temperature. Results suggest permanent changes to the dielectric constant which did not revert to the baseline. The paper concludes with recommendations for further studies into the cabling dielectric properties.

Keywords: Cavity perturbation, Dielectrics constant, Degradation Heating, IoT, PoE/PoE+, Power, Temperature.

1.0 Introduction

Remote powering over Ethernet is a long-established technology that continues to grow in application across many industries. The ability of the Ethernet to deliver Safe Extra Low Voltage (SELV) with limited power, over conventional Ethernet cabling is a major factor behind its successful growth. Besides, the rapidly evolving Internet of Things (IoT) technology, which requires Power over Ethernet (PoE), is further driving the growth. Moreover, the technology is necessary for network connectivity in home networking solutions and large building infrastructure management. Hence, there are now increasing applications of PoE in Building Automation Systems, which include; control systems for lighting, Heating, Ventilating, and Air Conditioning (HVAC) system, security system, energy-monitoring systems, etc. The new application areas have also promoted innovation, particularly in meeting the need of some of the power hungry devices. Such devices available today include, Thin clients, High power Access Points, Information kiosks, TVs, Pan/tilt/zoom IP cameras, Laptop computers, etc. According to a recent market forecast [1], by 2020, the PoE Technology will power about 9% of the entire desktop phones connected in an enterprise network and more than 80% of the Wireless Access Points (WAP) will rely on it. Its applications in other systems such as security cameras and access control will range between 20 and 50%.

The market trends highlight the need to enhance the Ethernet infrastructure, in order to cope with the increasing device count in the Local Area Network (LAN). This could mean that, the Power Sourcing Equipment (PSE) will have to increase power capacity per port, to support the connected power hungry devices or that the cable density should increase as a result of the increasing device count and user density.

Apparently, the Ethernet cables would increase and needs to be bundled from the telecommunication rooms before branching off to feed individual devices. Since the cables would also be used to deliver higher power, such as 100Watts, the consequential increase in the cable temperature, could affect the cable performance.

Additionally, with an increasing user density on the network, the rate of data transmission would increase, and this also may trigger a rise in temperature and demand for high bandwidth. As such, there is a need to improve the design of Ethernet cable so as to cope efficiently with the higher bandwidth and high power capabilities.

1.1 Background of Study

The benefits of powering network devices through their Ethernet connections are numerous, but the net effect is Joule heating of the cabling. Cabling Standards experts and different PoE vendors are well aware that 100Watts powering loads can impact the mechanical and electrical performance of the Ethernet cabling and connectivity [2, 3]. The heating problem is a known phenomenon and evidence supporting this has been well presented.

In the resistive heating studies presented in [4], there was a physical failure of the thermally insulated cable bundles (CB), as it exceeded the specified temperature limit of 60°C. Also, in the non-electrical heating tests presented in [5], mechanical failure of a cable bundle, due to high temperature and thermal cycling was reported. CBs are often deployed and distributed across multiple buildings; therefore, provision has to be made for the free dissipation of heat within the bundle. Otherwise, the cables' designed useful life may be reduced due to the accelerated ageing arising from high power deployment.
1.2 Motivation

In the imminent IoT networks, WAPs will require to function in increasingly remote locations and harsh environments. Variation in ambient temperature would also influence the mechanical behaviour of the cables. Temperature changes and environmental factors such as humidity, and localized heating may change the dielectric properties of the cabling, and this may lead to the modification of the designed transmission line coefficients [6]. Moreover, the installation of WAPs in the ceiling spaces suggests that cables will pass through walls. This can place a segment of the cable conductors under thermal stress, leading to impedance variations along the wires. It is also possible for the twisted pairs at that insulated portion to nest together or separate out due to excessive heating, changing crosstalk performance. In general, changes in conductor dimensions are expected to occur as a consequence of thermal variation. Any of these scenarios can affect the capacitance of the cable. In [5], permanent changes to some of the cable’s transmission parameters, such as attenuation and Return Loss were reported. As shown in figure 1.1, RL margin of Category 6 U/UTP was reduced, due to thermal cycling and heating within the maximum temperature of 70°C. This was a permanent change which did not revert to baseline. As these can be caused either by a change in the cable geometry, or degradation of the dielectric, or both, it is important to determine and isolate the key parameters that influence signal integrity in remote powered Ethernet systems.

One of the ways of assessing the degradation of the cable dielectric properties when subjected to changing environmental conditions, such varying temperature, is to study their frequency response under the varied thermal conditions. However, it may be impossible to examine this directly when the dielectrics have already been extruded on the copper conductors and are in use. As a result of this constraint, accurate test methods have to be employed for testing the dielectrics to provide an extensive dataset based on scenario simulations.

![Cat 6 U/UTP Return Loss performance](image)

Figure 1.1: RL measurements for Category 6 U/UTP

It is believed that this will provide adequate knowledge of how the cables perform as a function of cyclic heating, temperature, and frequency. In particular, the information obtained will serve as a guide to making decisions on the choice of dielectric materials that will not degrade the cabling performance.

To date, there have been published industry studies on the challenges of Ethernet cabling overheating and performance degradation. However, there is very little quantitative data about this interrelationship in the open literature. Specifically, there is no investigation into the effects of cyclic thermal stress on cable’s dielectric properties. Also, the influences of the selected dielectric constituents and cable design on the response are not, to our knowledge, available.

1.3 Objective of the study

Therefore, the focus of this study is to design and evaluate the accuracy of the Cavity Perturbation Method as a means of measuring the dielectric constant for some pure dielectric samples.

1.4 Structure of this work

The rest of this paper is organized as follows: Section 2 is a review of the literature. Section 2.1 gives a fundamental analysis of a basic transmission line. Section 2.2 describes different dielectric assessment methods. Then follows the main study for this paper, which is the implementation of the Cavity Perturbation theory (Section 3.0). Section 3.1 – Theoretical Analysis of the rectangular cavity design. Section 3.2 - Cavity modeling and 3.3 deals with the cavity construction. Section 4 describes the cavity testing and the dielectric baseline measurements. Section 5 - dielectric testing with heating and cooling cycles. Section 6 is a discussion of the results obtained from section 5. Section 7 concludes the paper and suggests further studies on the investigations of the dielectric materials with additives.

2.0 Theory

2.1 Theory of a basic transmission line

The analysis of the signal transmission parameters can be viewed from the conceptual idea of the transmission line. The initial values of the signal transmission parameters are specified when cable dimensions are determined, and materials are processed. These initial values, however, do not quantify the performance of the cables in the real applications. Additionally, some of the transmission parameters are not measured but determined indirectly. For example, Attenuation and Return Loss are sometimes determined from impedance and resistance [7]. The mutual capacitance of a twisted pair is specified in the cable’s data sheet, but the mutual capacitance measured in practice depends on the dielectric constant of the insulator between the two conductors and the proximity of the conductors. Any changes to the material properties result in variations in the signal transmission performance. The speed at which a signal travels along a cable depends on the properties of the insulation. The two material properties that affect the signal transmission are dielectric constant and the dissipation factor [7].

In the equivalent circuit for a short length of a transmission line shown in Figure 1.2, L represents the inductance per unit length; C represents the capacitance per unit length.

![Transmission Line Model](image)

Figure 1.2: Transmission Line Model

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As shown in equation 2.1.1, these two primary parameters can be used to determine the characteristic impedance ($Z_0$) for a low loss transmission line (where $R$ and $G$ are vanishingly small in comparison with the reactances).

$$Z_0 = \sqrt{\frac{L}{C}} \Rightarrow \sqrt{\frac{\mu}{\varepsilon}}$$ (2.1.1)

For a twisted pair, the per unit length inductance ($L$) is calculated

$$L = \frac{\mu_0 a}{\pi} \cosh^{-1} \left(\frac{\pi s}{d}\right)$$ (2.1.2)

and per unit length capacitance is calculated as

$$C = \frac{\pi \varepsilon_0 \varepsilon_A}{\cosh^{-1} \left(\frac{\pi s}{d}\right)}$$ (2.1.3)

as compared to a bulk capacitance which is calculated as

$$C = \frac{d}{d_s}$$ (2.1.4)

At high frequencies, the series resistance and the shunt resistance can be ignored because the reactance dominates. Since there is no reason why the permeability ($\mu$) should change, the inductance term in equation (2.1.1) is not discussed further in this study.

However, capacitance is a function of geometry (conductor diameter & spacing) and the material properties such as the electric permittivity. Hence, the focus in equation (2.1.1) is on the electric permittivity. Electric permittivity is a material property, which affects the propagation of the electric field when an alternating voltage is applied to a material. Electric permittivity is a complex number, which is given in equation (2.1.5).

$$\varepsilon = \varepsilon' - j \varepsilon''$$ (2.1.5)

And the loss tangent is given as $\tan \delta = \frac{\varepsilon''}{\varepsilon'}$ (2.1.6)

where the real part, $\varepsilon'$ - Represents the energy stored within the medium and the imaginary part, $\varepsilon''$- energy dissipation (loss) within the medium.

The real part of permittivity $\varepsilon' = \varepsilon_r \varepsilon_0$ (2.1.7)

Dielectric constant $\varepsilon_r = \frac{\varepsilon'}{\varepsilon_0}$ (2.1.8)

where $\varepsilon_0$ is the permittivity of free space $\approx 8.85 \times 10^{-12}$ F.m$^{-1}$, and $\varepsilon_r$ is the dielectric constant or the relative permittivity of dielectric materials [9].

2.2 Dielectric properties assessment methods

There are different techniques for assessing the permittivity of polymeric materials. These include analytical approaches, numerical methods, and microwave measurement techniques. The measurement techniques are in two broad categories, the transmission-reflection techniques (non-resonant), and the resonance techniques.

The non-resonance techniques include the free space method, coaxial probe method, waveguide method, parallel plate method, etc. The non-resonance techniques provide measurement capability over a wider frequency range, but have the limitation of lower measurement accuracy, whereas, the resonant techniques provide more measurement accuracy but measure the dielectric properties at a single or few discrete frequency points [9]. Thus resonance methods are often preferred.

There are two main resonance methods for characterizing the dielectric properties; these methods are the cavity perturbation method and the dielectric resonator method. The cavity perturbation method allows dielectric samples of different geometries to be tested, but the dielectric resonator method works only on samples with either rectangular or round shape. Another advantage of the cavity perturbation method is its simple calculation process for obtaining the complex permittivity [10] as compared to the computer algorithm used in the dielectric resonator method.

The cavity perturbation method has been very useful in the specification acceptance, manufacturing control, research, and development of different electronic components [10]. Many researchers have also adopted it for the measurements of high loss materials and low loss materials. According to [11], the resonant cavity technique is the most accurate method for dielectric properties measurements and is therefore adopted in this study.

3.0 Method and Designs

This section presents the design procedure for the construction of a rectangular resonant cavity that is capable of operating within 2.2 - 3.3GHz range. The design process begins with the analytical expression for a TE$_{101}$ mode rectangular cavity. Followed by the simulation of the cavity using CST Microwave Studio. After that, the rectangular cavity was manufactured in-house, tested and verified to be working according to the designed specifications. It was after that calibrated following standard procedure.

3.1 Theoretical analysis of the cavity design

Depending on the cavity dimensions and the Electromagnetic boundary conditions, a different number of modes can exist inside a cavity. For instance, consider a TE$_{10m}$ rectangular cavity, its dimensions, and the integral number of half waves and their directions of propagation as terminated by the walls of the cavity, the resonant frequency of a given mode is determined using equation 3.1 [11].

$$f_{mn} = \frac{c}{2 \sqrt{\mu_0 \varepsilon_0}} \sqrt{\left(\frac{l}{a}\right)^2 + \left(\frac{m}{b}\right)^2 + \left(\frac{n}{d}\right)^2}$$ (3.1)

Where $l$, $m$, $n$ are the mode numbers. $a$, $b$ and $d$ are the width, height, and the length of the rectangular cavity respectively. $c$ is
the speed of light in free space, \( \mu_0 \) is the permeability of free space and \( \epsilon_0 \) is the permittivity of free space.

Figure 3.1: Scheme of the rectangular cavity

Assume the cavity rejects all other modes in the cavity except the fundamental mode \( \text{TE}_{101} \) and operates at 2.45GHz, then the width of the cavity is determined by equation 3.2.

**Width of the cavity (a)**

\[
a = \frac{c}{2.45 \times 10^8 \sqrt{\varepsilon_0}} = \frac{3 \times 10^8}{2.45 \times 10^8} = 86mm \quad (3.2)
\]

Note that; for \( \text{TE}_{101} \rightarrow \text{TE}_{10m} \), \( l \) represents the number of half-waves across the cavity. As indicated on the scheme of the cavity in figure 3.1, \( a \) is only one half wavelength across the cavity (x-direction). The cutoff wavelength is:

\[
\lambda_c = \frac{2}{\sqrt{(\frac{l}{2})^2 + (\frac{b}{2})^2}} \quad \lambda_c = \frac{2}{\sqrt{(\frac{86}{2})^2 + (\frac{43}{2})^2}} = 172mm \quad (3.3)
\]

**Height of the cavity (b)**

\[
\frac{a}{b} = 2 \quad b = 43mm \quad (3.4)
\]

Similarly, for \( \text{TE}_{101} \rightarrow \text{TE}_{10m} \), \( m \) represents the number of half-waves from the top to the bottom of the cavity. In this case, \( m \) is zero.

**Length of the cavity (d)**

It is required that the following assumptions be met for the length of the rectangular cavity.

\[
b < a < 2b
\]
\[
a > b < d
\]

The length of the rectangular cavity (d) was chosen to be 88mm.

Note that; \( n \) accounts for the number of waves along the cavity. For \( \text{TE}_{101} \rightarrow \text{TE}_{10n} \), \( n \) is just one. (\( n \) must be a positive integer)

Hence, the resonant frequency of the fundamental (\( \text{TE}_{101} \)) mode operating in the cavity with the above dimensions is determined by equation 3.1.

\[
f_{10n} = \frac{c}{2\sqrt{\mu_0 \varepsilon_0}} \sqrt{\left(\frac{l}{2}\right)^2 + \left(\frac{m}{b}\right)^2 + \left(\frac{n}{d}\right)^2}
\]

Since the resonant frequency of a particular mode must be higher than its cutoff frequency. Then, the cutoff frequency of the first-order mode \( \text{TE}_{10} \) is determined by equation 3.5.

\[
f_{c10} = \frac{c}{2\sqrt{\mu_0 \varepsilon_0}} \sqrt{\left(\frac{1}{2}\right)^2 + \left(\frac{1}{86}\right)^2} = 2.4GHz
\]

\[
f_{c10} = 150\sqrt{\left(\frac{1}{88}\right)^2 + (0)} = 1.7GHz \quad (3.5)
\]

3.2 Cavity Modeling

The goal of this section is to model the dimensions described in the previous section before the construction of the actual cavity. Also, to setup a model that will allow the visualisation of the perturbed Electric field inside the cavity. This simulation is necessary because it will provide guidelines for the implementation of the experimental results. Also, the dimensions for the dipole can be varied to optimize the design.

Given a resonant frequency, the physical dimensions of the cavity had to be large enough to contain the sample and include the antennas at the frequency of interest. It must also allow sufficient modes to be supported within the structure. As a result, the dimensions of the rectangular cavity were largely determined by equations (3.2) to (3.4). Also, by following the limits imposed by the test document, all the conditions were met by having a structure of \( 88 \times 86.36 \times 43.18 \) mm.

Using the various building blocks available in CST Microwave Studio, a rectangular cavity was modelled as shown in figure 3.2. Brass material was chosen for the cavity and PEC for the energy coupling device. To obtain the resonant frequency calculated in equation 3.5, the length of the two dipoles was varied and optimized. As a result of the optimization, the physical length of the dipoles used was about 10mm, which is shorter than the natural resonant length of 30mm (one-quarter wavelength).

Figure 3.2: Model of the rectangular cavity

After the modeling of the cavity, Electromagnetic boundary conditions were set-up. The simulation was performed using a time domain solver and a frequency sweep of 2-3GHz. The perturbed field inside the cavity is shown in figure 3.3.
3.3 Material selection and the construction of the cavity

The Quality factor (Q-factor) of an empty resonant cavity defines the sharpness of its resonance curve against frequency. It is a function of the conductivity of the cavity inside wall. High Q-factor (Q) indicates the low electrical loss of the cavity. The Q factor of a cavity can be enhanced by using a perfect electrical conductivity (PEC). However, in the absence of a PEC, metallic conductors such as copper, silver, aluminium, and brass are used. Copper and silver are expensive; aluminium is difficult to solder; brass material was chosen for the construction of the rectangular cavity. Brass has no soldering problem but has lower electrical conductivity compared to aluminium, copper, and silver. Brass was used so that its six uniform plane surfaces can be soldered together to produce a well-shaped rectangular cavity. Additionally, to remove any surface roughness and enhance the Q of the cavity, the inside of the cavity was highly polished with a metal polish.

Energy coupling device

The guidelines of the ASTM test B allow the use of iris holes, probes, or loops for the energy coupling inside the cavity. Dipoles, made from copper were used instead of the iris holes. Holes were avoided from complicating the resonant behaviour of the cavity.

Besides the influence of materials and holes on the cavity resonance, the length of the energy coupling device also has an impact. The length of the coupler obtained from the simulation was used for the two dipoles inserted into the cavity.

4.0 Cavity and the baseline dielectric testing

The assessment of the dielectric constant for various samples was performed using the cavity perturbation method. For the successful implementation of the cavity perturbation technique, two primary factors have to be considered. (1) The size of the sample (2) The sample placement inside the cavity. These two factors were taken into account for the assessments of dielectric constant in this study. The baseline values of the dielectric constant were investigated and established first in this section. Followed by the thermal cycling of the samples in section 5.

4.1 Experimental setup

The rectangular cavity designed for the dielectric properties measurements is shown in figure 4.1.

As can be seen, two coaxial cables are connected from the ports of the ZVL network analyzer to the resonant cavity. The cavity has no holes around it. As a result, no thermocouple sensor was introduced into the cavity for the purpose of temperature measurements. The dielectric heating system and the temperature acquisition system were placed separately from the cavity; this was to prevent the effects of the heat contribution on the resonance of the cavity.

4.2 Dielectric samples and sample volume

The size of the perturbation sample used for dielectric measurements has an influence on the sensitivity of the measurements. For this reason, the primary requirement of the test guidelines is that; the volume of the perturbation sample should be relatively small compared to the volume of the cavity. Also, the diameter of a rod sample, in particular, must be 10% or less when compared to the wavelength of the measurement frequency.

In [12], it was suggested that the diameter of a thin sample should be ≤0. 25a. Also, [13] concluded that the maximum sample volume for dielectrics with different geometries follows the order of strip/disk> sphere>rod/bar.

The samples under test (SUT) in the study, have different geometries and different dimensions. As shown in figure 4.2, six out of the seven samples are a rod, while the remaining one is a short length of a twisted pair. The diameter of the rod samples is less than 10% of the wavelength at the measurement frequency. Also, the height of the rod samples is the same as the height of the rectangular cavity. The volume of the samples and the volume ratios are listed in Table 1.

4.3 Verification of assumptions before dielectric testing

The primary requirement for accurate dielectric property measurements is to place the sample in a region of a uniform E-field inside the cavity. The assumption is that the presence of a small dielectric sample placed in the field will not significantly change the field configuration inside the cavity. That is, the shift
in the resonant frequency of the loaded cavity will be negligibly small when compared to the resonant frequency of the unloaded (empty) cavity. However, the amount of the shift in the resonant frequency was suggested to be $\leq 10^{-3}$ in [13].

Before the testing and the measurements of the dielectric samples were conducted, a region for the accurate dielectric property measurements was located inside the cavity, with the aid of a removable template shown in figure 4.3. This was placed inside the cavity to obtain the resonance curves of a single PTFE rod; that was introduced into different locations inside the cavity.

Before each measurement, the calibration of the network analyzer was performed by selecting TOSM calibration type with the standard calibration kit. Then, the scattering parameter ($S_{21}$) was measured with the network analyzer to obtain the resonant curve of the removable template. After that, the resonance curves for the PTFE in all the locations were obtained one after the other, under approximately the same room temperature. The different resonances of the loaded cavity as a function of the PTFE’s placement positions are shown in figure 4.4. As indicated, the resonance of the PTFE rod placed in the center of the cavity appears to be the last resonance; from the resonance of the unloaded cavity. That is, the resonance of the PTFE placed at the center of the cavity experienced the highest frequency shift.

Using equation 4.1 [10], the dielectric constant of the single PTFE in various locations inside the cavity was calculated. The dielectric constant obtained for different locations are shown in figure 4.5.

$P = \text{Relative Permittivity (Dielectric constant - } \varepsilon_r)$

$V_c = \text{Volume of the cavity}$

$V_s = \text{Volume of the sample}$

$f_{rc} = \text{Resonant frequency of the unloaded cavity}$

$f_{rs} = \text{Resonant frequency of the loaded cavity}$

As indicated in figure 4.5, the highest and the most accurate dielectric constant obtained for PTFE at room temperature was 2.16. This is in good agreement with the values reported in the published literature [16].

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>$S_{21}$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.32e+9</td>
<td>2.33</td>
</tr>
<tr>
<td>2.34e+9</td>
<td>2.34</td>
</tr>
<tr>
<td>2.36e+9</td>
<td>2.35</td>
</tr>
<tr>
<td>2.38e+9</td>
<td>2.36</td>
</tr>
</tbody>
</table>

Figure 4.4: Resonances of PTFE placed in different locations

Figure 4.5: $\varepsilon_r$ of the PTFE placed in different positions in the cavity

Figure 4.6: Showing the field distribution inside the cavity
4.4 Measurements of dielectric properties

Testing of the baseline samples

The network analyzer was calibrated to avoid errors in the measurement results. Also, the coaxial cables connecting the cavity and the network analyzer were constrained in a fixed position. After the calibration, the S21 parameter for the unloaded cavity was measured first at room temperature. Then, samples shown in figure 4.2 were tested. The measurements were taken at the same ambient temperature of ~21°C before the first heating cycle began. The resonant frequency of the unloaded (empty) cavity was measured at 2.4GHz; this is indicated in figure 4.7. The rest of the curves are the baseline resonances of the SUT.

Figure 4.7: Resonances of samples with different volume sizes

The values of the baseline measurements were calculated as per equation 4.1; these are shown in Table 1

Table 1: Baseline dielectric constant of the SUT in comparison with published results.

<table>
<thead>
<tr>
<th>Samples under test</th>
<th>Vc (mm)</th>
<th>(Vc/Vs) (mm)</th>
<th>εr</th>
<th>Published Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene</td>
<td>3391.79</td>
<td>9.73E-03</td>
<td>2.21</td>
<td>2.2 [14]</td>
</tr>
<tr>
<td>PVC</td>
<td>3391.79</td>
<td>1.03E-02</td>
<td>2.97</td>
<td>2.8 [15]</td>
</tr>
<tr>
<td>PTFE 6mm</td>
<td>1221.04</td>
<td>3.72E-03</td>
<td>2.16</td>
<td>2.1 [16]</td>
</tr>
<tr>
<td>PTFE 10mm</td>
<td>3391.79</td>
<td>1.03E-02</td>
<td>2.19</td>
<td>2.1 [16]</td>
</tr>
<tr>
<td>HDPE</td>
<td>3391.79</td>
<td>1.03E-02</td>
<td>2.43</td>
<td>2.35 [16]</td>
</tr>
<tr>
<td>Deionized water</td>
<td>1.61</td>
<td>5.00E-06</td>
<td>80</td>
<td>4.88 [17]</td>
</tr>
<tr>
<td>Twisted Pair</td>
<td>249.97</td>
<td>7.62E-04</td>
<td>4.8</td>
<td>-</td>
</tr>
<tr>
<td>Unknown</td>
<td>3391.79</td>
<td>1.03E-02</td>
<td>3.57</td>
<td>-</td>
</tr>
</tbody>
</table>

The εr values for the samples with the same geometry and volume size are shown in figure 4.8.

If the order of the resonances shown in figure 4.7 is related to the information in table 1, it can be seen that the shift in the resonances of the samples having the same geometry and volume size can be correlated to their material property (εr) plotted in figure 4.8.

5.0 Assessment of dielectric constant with heating and cooling cycles

Experimental constraints

The experiment was set up in a laboratory with no active climate control. Also, relative humidity during the experiment was about 52%. The heating rate of the dielectrics was the same, but the heating period was not. Fast acquisition of the S21 parameter could not be performed when the samples were at the peak of 70°C. As a result, the dielectric constant values were calculated for the warm samples at an unknown temperature below 70°C.

5.1 Heating of the samples

The samples were heated in a conventional oven with an automatic temperature control. For a uniform and the slow heating of the dielectric samples, a heating rate of 1°C per minute was set in the electric oven. When the temperature had reached a maximum of 70°C, the oven control stays on to maintain the temperature set-point until the oven is manually turned off. 11 heating cycles were carried out on the SUT. The temperature profile for one of the heating cycles is shown in figure 5.0.

Figure 5.0: Temperature profile of the first heating cycle

5.2 Measurements of the samples after the heating cycles

For each measurement, the network analyzer was reset and calibrated. As discussed in the earlier section, the dielectric samples were measured first at room temperature before the first heating cycle began. Then, after the heating had reached a temperature of 70°C, the samples were quickly moved from the oven into the cavity for the S21 measurements. After that, samples were removed from the cavity and placed in an area that is free of dust and moisture for the natural cooling of the samples. Then,
the baseline samples for the next heating cycle were measured, and the heating process started again, until the last cooling cycle (cycle 11). Note that, measurements of the samples were performed one after the other. Also, the room temperature was recorded at each time the samples were measured. The values of \( \varepsilon_r \) was calculated using equation 4.1.

6.0 Result analysis

The effects of temperature and thermal cycling on the dielectric constant of some samples are presented in this section.

6.1 Unknown rod sample

This rod sample is referred to as unknown because the material is an unspecified type of plastic. Other rod samples were of clearly defined types.

The resonant frequency curves measured for the unknown sample, both for the heating and the cooling cycles are shown in figure 6.1a. As shown, the black curve represents the resonance of the unloaded (empty) cavity while the gray curve shows the magnitude of \( S_{21} \) due to the insertion of the unknown sample into the cavity. From the gray curve, it is apparent that the introduction of the sample caused a resonant frequency shift to below the resonance of the unloaded cavity. Additionally, the change in the magnitude of the \( S_{21} \) can be observed.

The effect of temperature on the dielectric constant of the unknown sample can be seen from the first heating cycle. The value of \( \varepsilon_r \) increased due to heating, and then decreased progressively due to the effect of the thermal cycling.

Figure 6.1b: \( \varepsilon_r \) of the unknown sample due to thermal cycling

6.2 Short length of a twisted pair sample

Figure 6.2a and 6.2b are the results for the twisted pair sample. An interesting observation in the resonant frequency curves shown in figure 6.2a is the distinct magnitude of the \( S_{21} \) that was measured after the first heating cycle. As can be seen, the magnitude of the \( S_{21} \) obtained from the rest of the heating and the cooling cycles remained above that of the baseline sample, except the one obtained after the first heating cycle.

Figure 6.2a: Resonances of the twisted pair sample

Figure 6.2b also presents the \( \varepsilon_r \) of the twisted pair sample when heated and cooled repeatedly. As shown, a reduction in the \( \varepsilon_r \) value of the twisted pair is obvious for the first heating and cooling cycle. After that, a distinct increase in the \( \varepsilon_r \) can be seen for the second heating and the cooling cycle. This later reduced and remained fairly constant until the heating cycles 10, when it started to converge to a constant value.

Figure 6.2b: \( \varepsilon_r \) of the twisted pair sample due to thermal cycling
6.3 High-Density Polyethylene (HDPE) rod sample

Figure 6.3 shows the dielectric constant of the High-Density Polyethylene (HDPE) obtained after each cycle. A reduction in the dielectric constant of HDPE was observed within the first cycle. Further reduction is also apparent until the fourth cycle when the value converged to a constant value.

![Figure 6.3: εr of the HDPE rod sample due to thermal cycling](image)

6.4 PTFE rod sample (6mm diameter)

Figure 6.4 shows the $\varepsilon_r$ of the PTFE (6mm diameter) sample. The values plotted were measured near the room temperature after each heating cycle. The $\varepsilon_r$ of the PTFE 6mm sample remained unchanged up to the 7th cycle. After the 7th cycle, an increased in $\varepsilon_r$ was observed for the 8th cycle. This increase was also observed for the 10th and the 11th cycle.

![Figure 6.4: εr of the PTFE rod sample due to thermal cycling](image)

6.5 PTFE rod sample (10mm diameter)

Figure 6.5 shows the $\varepsilon_r$ of the PTFE rod (10mm diameter) sample. The values plotted were measured after each heating cycle. That is, when the sample was warm (below 70°C). As can be seen, a noticeable reduction in the $\varepsilon_r$ occurred within the first 3 heating and cooling cycles. Afterwards, the value remained relatively constant.

![Figure 6.5: εr of the PTFE rod sample due to thermal cycling](image)

6.6 PVC rod sample

Figure 6.6 shows the $\varepsilon_r$ of the PVC rod sample. The values plotted were measured near the room temperature after each heating cycle. The major reduction in the $\varepsilon_r$ of the PVC occurred within the first two cycles. Afterwards, the $\varepsilon_r$ remained fairly constant.

![Figure 6.6: εr of the PVC rod sample due to thermal cycling](image)

7.0 Conclusion

The dielectric constants of some pure dielectric samples were examined at 2.4GHz, using the Cavity Perturbation Method of the ASTM D2520-13. This was done using a brass cavity designed in CST Microwave Studio, and shown experimentally to have a suitable field profile. The assumptions of the cavity perturbation theory on which the ASTM test is based were verified numerically and experimentally. The dielectric constant of samples of different geometries was examined with heating and cooling over a temperature range of +20°C to 70°C Celsius. Results suggest permanent changes to the dielectric constant which did not revert to the baseline. Further work will be required to study commercially available dielectrics presently utilized in cable manufacture. This will facilitate the characterization of the capacitive properties of cables as a function of temperature, which it is believed to dominate the reactive component of cable impedance.

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References


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