COMPLEX PERMITTIVITY DETECTION OF ORGANIC CHEMICALS

BY RF RESONANT CIRCUIT

An Undergraduate Research Scholars Thesis

by

JIAWEI XIAO

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by
Research Advisor: Dr. Kamran Entesari

May 2015

Major: Electrical Engineering
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>2</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>3</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>I INTRODUCTION</td>
<td>4</td>
</tr>
<tr>
<td>Complex Permittivity</td>
<td>4</td>
</tr>
<tr>
<td>Conventional Measurement</td>
<td>6</td>
</tr>
<tr>
<td>II METHODS</td>
<td>8</td>
</tr>
<tr>
<td>System Functionality</td>
<td>8</td>
</tr>
<tr>
<td>Sensing Element Design</td>
<td>10</td>
</tr>
<tr>
<td>III RESULTS</td>
<td>14</td>
</tr>
<tr>
<td>Simulation Result</td>
<td>14</td>
</tr>
<tr>
<td>Cole-Cole Model</td>
<td>17</td>
</tr>
<tr>
<td>IV CONCLUSION</td>
<td>18</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>19</td>
</tr>
</tbody>
</table>
ABSTRACT


Jiawei Xiao
Department of Electrical and Computer Engineering
Texas A&M University

Research Advisor: Dr. Kamran Entesari
Department of Electrical and Computer Engineering

A material’s dielectric properties are determined by its molecular structure, other properties of interest such as the interactions with an applied electromagnetic field can be correlated to the dielectric properties. Dielectric detection has various applications in many areas such as human health, food safety, oil industry etc. The techniques for dielectric constant detection are basically classified into time-domain and frequency-domain. The time-domain has its advantage of detecting the permittivity versus frequency at once. However, this method has its inherently disadvantage due to instability in the time axis including jitter, time drift and variation of the sweep speed in the oscilloscope. In this research thesis, we implement a RF system to detect the complex permittivity of organic chemicals by measuring the changes in resonant frequency of the system. All the results will be presented in the following several chapters.
DEDICATION

I dedicate my work to my family and friends. A special feeling of gratitude to my loving parents, Xiaojin Xiao and Aihua Song whose words of encourage and push for tenacity ring in my ears, I will never be able to study at Texas A&M University without your support.

I also dedicate my work to many friends who have support me throughout my study. I will always appreciate all they have done, and I promise I will keep working hard.
ACKNOWLEDGEMENTS

First and foremost, I would like to take this opportunity to express my deepest gratitude to my research advisor, Dr. Kamran Entesari, for providing me this great opportunity to learn more in RF field. Ever since the first day when he taught me Electronic Circuits, Dr. Entesari has been an outstanding mentor and role-model. His enthusiasm for research and teaching is inexhaustible. His brilliant insight, patient guidance throughout my study helped to lit my route of my future study. It is my honor to work with him and I will cherish this valuable experience.

I want to thank the Department of Electrical and Computer Engineering, Texas A&M university for providing me a platform to pursue my research interest and giving me award to honor my research achievements as an undergraduate.
CHAPTER I
INTRODUCTION

Complex Permittivity

In electromagnetism, absolute permittivity is the measure of the resistance that is encountered when forming an electric field in a medium. Permittivity is a measure of how an electric field affects a dielectric medium. The permittivity of a medium describes how much electric field is generated per unit charge in that medium. In SI units, permittivity $\varepsilon$ is measured in farads per meter (F/m), and $\varepsilon_0 = 8.854 \times 10^{-12} F/m$ is the vacuum permittivity.

As opposed to the response of a vacuum, the response of normal materials to external fields generally depends on the frequency of the field [1]. This frequency dependence reflects the fact that a material’s polarization does not respond immediately to an applied field. The response must always be causal which can be represented by a phase difference. For this reason, permittivity is often treated as a complex function of the angular frequency of the applied field. The definition of permittivity there becomes

$$D_0 e^{-i\omega t} = \hat{\varepsilon}(\omega) E_0 e^{-i\omega t} \quad (I.1)$$

where $D_0$ and $E_0$ are the amplitudes of the displacement and electric fields respectively.

A material’s complex permittivity is usually normalized to the permittivity of a vacuum. The complex permittivity consists of two parts, the real part and the imaginary part. The real part of complex permittivity $\varepsilon'$ is used to measure the energy stored in the material, and it is also called the dielectric constant. The imaginary part of complex permittivity $\varepsilon''$ characterizes the energy
loss of the material, and it is also called the loss factor. Thus the complex permittivity can be express as the following equation:

\[ \tilde{\epsilon}(\omega) = \epsilon'(\omega) + i\epsilon''(\omega) \]  

(I.2)

where \( \epsilon' \) is the real part of the complex permittivity and \( \epsilon'' \) is the imaginary part of the complex permittivity.

[Image: Fig. I.1: Complex Permittivity of Water VS. Frequency]

Take water as an example, Fig.I.1 illustrates how the complex permittivity of water varies with the frequency of the applied electric field.

The water molecule consists of two hydrogen atoms and one oxygen atom, when there’s no electric field applied, water molecules will take on a random orientation. The bonding
mechanism leads to the hydrogen side of the water molecule is more positive and the oxygen side is more negative [2]. Therefore, if a constant electric field is applied to water, the water molecules will tend to orient with the electric field, causing the water to have a specific capacitance.

At low frequency, the water molecules can follow the applied electric field to get the maximum value of $\varepsilon^\prime$, as it is shown in the picture above, the flat band reflects the dielectric constant of water. This polarization is also a form of energy storage, under this circumstance the positive and negative ions are oriented by the electric field and the corresponding electric current represents to an energy loss [3].

With the frequency increasing, the polarization of water molecules can no longer keep up with the frequency of the electric field. This will result in higher energy losses and less energy storage in water molecules.

As the frequency increases higher and higher, we can see that the water molecules no longer respond to the increasing frequency of the electric field. Thus for most materials, the complex permittivity is usually measured below this corner frequency. This corner will also help us to determine the resonant frequency we designed for the RF system.

**Conventional Measurement**

In industry world, dielectric constant can be measured both in time-domain and frequency-domain. The time-domain dielectric spectroscopy is based on transmission line theory in the
time domain that aids in the study of heterogeneities in coaxial lines according to the change of the shape of a test signal. As long as the line is homogeneous the shape of this pulse will not change. But, in the case of heterogeneity in the line, the signal is partly reflected from the air-dielectric interface and partly passes through it [4], [5]. Dielectric measurements are made alone a coaxial transmission line with the sample mounted in a sample cell that terminates the line. Problems of accuracy and sensitivity associated with this method is obvious, this time-domain system inherently have various general hardware problems due to instability in the time axis including jitter, time drift and variation of the sweep speed in the oscilloscope.

Previous researches have demonstrated that compared with the time-domain techniques, the frequency-domain techniques have great advantages. Measurements are setup in minutes and made in seconds providing real time data. Depending on measurement technique, measurements can be non-destructive since no sample preparation is required, and even non-contacting with free-space techniques.

In Chapter II, we will introduce the spectroscopy system to measure the complex permittivity in frequency domain. It will discuss and present the functionality, design and implementation of the system. In Chapter III, it will present the simulation result including both schematic simulation and optimized EM 3D simulation results. Measurement results will also be provided to compare with the simulation results, dielectric constant calculation will be done based on the measurement data.
CHAPTER II

METHODS

System Functionality

The proposed system for complex permittivity detection is a simplified microwave resonator, and the equivalent electrical model of this microwave resonator is a parallel RLC resonant circuit. For each resonant circuit, it has a resonant frequency. Electrical resonance occurs in an electric circuit at a particular resonant frequency when the impedance of the circuit is at a maximum in a parallel circuit [6]. The following figure shows the equivalent circuit model of the microwave resonator coupled to a transmission line.

![Figure II.1: Equivalent circuit model of the microwave resonator](image)

Figure II.1: Equivalent circuit model of the microwave resonator
The RLC circuit is obtained from the duality of the series circuit, which means that the circuit is probed with a current source $i_s$, thus the admittance of the circuit reaches the minimum value at resonance. For the parallel RLC circuit, the resonant frequency $\omega_0$ is given by

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

(II.1)

where $L$ is the value of the inductor and $C$ is the value of the capacitor. The attenuation $\alpha$ of the parallel RLC circuit is given by

$$\alpha = \frac{1}{2RC}$$

(II.2)

We use the resistor and capacitor as the sensor exposed to the material-under-test (MUT), the effect of the complex permittivity of the MUT on the sensor may result in changing the value of the resistor and capacitor. The value the sensing capacitor $C(\omega)$, is proportional to the real part of the MUT’s complex permittivity $\varepsilon'(\omega)$ and the value of the sensing resistor $R(\omega)$, is inversely proportional to the imaginary part of the MUT’s complex permittivity $\varepsilon''(\omega)$.

When the MUT is applied on the sensing capacitor and resistor, it will lead to the shift of resonant frequency $\omega_0$ and change of attenuation $\alpha$. We can calculate the value of the sensing capacitor and resistor based on II.1 and II.2, so that we can determine the complex permittivity of the MUT.

In order to make the system have more selectivity, a high quality factor (Q factor) is required for this system. To make the circuit have a higher Q factor and lower loss, we chose to model the parallel RLC circuit to a microwave resonator.
Sensing Element Design

Figure II.2: Schematic of the RLC Resonator

Figure II.3: Schematic of the equivalent Microwave Resonator
The schematic of the RLC circuit is presented above, the RLC resonator has a resonant frequency at 2G Hz with a Q factor of 30.

Figure II.3 shows the equivalent schematic of the microwave resonator, it has the same functionality as the parallel RLC resonator with higher Q factor and lower loss.

In order to reduce the parasitic effect, the sensing element is a planar microwave cavity on a two-layer 0.254-mm-thick RT-5880 substrate (dielectric constant $\varepsilon' = 2.20$, and dissipation factor $\tan\delta = 0.0009$). The following figures shows the details of the sensing element.

Figure II.4: 3D view of the Microwave Resonator
Figure II.5: Top view of the Microwave Resonator

Figure II.6: Coupling Capacitor for the Resonator
Figure II.4, II.5 and II.6 above illustrate the details of the sensing element, the sensing capacitance changes proportional to the value $\varepsilon'(\omega)$ of the material put on the top of the sensor. However, the resistance is inversely proportional to the value $\varepsilon''(\omega)$ of the MUT. The values of the capacitance and resistance at high frequency can be accurately determined by electromagnetic simulations.
CHAPTER III
RESULT

Simulation Result:

Figure III.1: Schematic Simulation Result on ADS

Figure III.2: Momentum Simulation Result on ADS
As we can see from Figure III.1 and III.2 above, we can see that the resonant circuit reaches a resonant frequency at 2 GHz with a very high Q factor, the S11 parameter at 2 GHz is 1.426 dB. When added effect of ambient electromagnetic and the substrate, we can see that the momentum simulation result keeps constant with the schematic result.

We build the 3-D model of the resonant cavity in Ansoft HFSS, the 3-D EM simulation and the system optimization was done by Ansoft HFSS. The results will present as following.

Figure III.3: 3-D EM Simulation Result on HFSS
After adding the electromagnetic effect and RT 5880 substrate, we can see that the resonant frequency of the system has a slightly shift. Because the 3-D simulation is the system performance in practice, in order to make the cavity system have better performance and be close to the ideal simulation result, we did some optimization for the cavity system. The 3-D EM simulation researches a resonant frequency at 1.9940 GHz with at Q factor of \(8.5e+005\), the S11 parameter at 1.9940 GHz is 4.34 dB.
**Cole-Cole Model:**

The Cole-Cole model has been successfully used to describe the experimental data for dielectric constant for many materials as a function of frequency. The Cole-Cole model is given by the following equation:

\[
\varepsilon^*(\omega) - \varepsilon_\infty = \frac{\varepsilon_s - \varepsilon_\infty}{1 + (i\omega\tau)^{-\alpha}}
\]  

(III.1)

As we can see in this equation, the dielectric constant mainly depends on four parameters, the static dielectric constant \( \varepsilon_s \), the dielectric constant at infinite frequency \( \varepsilon_\infty \), the exponent factor \( \alpha \) and the relaxation time \( \tau \). The static dielectric constant \( \varepsilon_s \) and the dielectric constant at infinite frequency \( \varepsilon_\infty \) can be measured from the experimental data, the factor \( \alpha \) and the relaxation time \( \tau \) can be derived from the best fitting experimental data. However, in practice, in most cases \( \varepsilon_s \) and \( \varepsilon_\infty \) can’t be directly obtained because it is extremely to measure them at very low and high frequencies.
CHAPTER IV

CONCLUSION

In this paper, we considered to use the microwave resonator to measure the complex permittivity of chemical liquids. The system modification and EM simulation were matched with the design specifications. The complex permittivity of the chemical liquids can be calculated by the Cole-Cole equation. Due to a very high expense of PCB fabrication with the material of RT5880, the experimental data cannot be presented at this point. Future works will involve the experimental data measurements and calculation.
REFERENCES


