

Dielectric Properties of Salt and Sugar Solutions at 200 MHz – 10 GHz

Jessica Chong

January 2022

A report submitted as partial fulfilment
of the requirements of
PHYS 437A

University of Waterloo

Abstract

With recent developments in technology, the low-cost and non-invasive monitoring of food quality has been a popular subject of study. The dielectric properties of various concentrations of salt and sugar dissolved in distilled water are measured using an open-ended coaxial probe technique over the frequency range 200 MHz to 10 GHz. The conducted literature survey indicates a decrease in the value of the dielectric constant and an increase of the dielectric loss with an increase in concentration over this frequency range. Since the dielectric properties vary, the survey indicates that it is possible to develop a radar that can accurately detect these concentrations and the slight variances in a food product. Inconsistent results have been achieved using the DAK-TL 3.5 probe that show drastically opposite trends of theoretical values.

Contents

Abstract	ii
List of Tables	iv
List of Figures	v
Acknowledgements	vi
1 Introduction	1
1.1 Theoretical Background	2
1.1.1 Dielectrics in an Applied Electric Field	2
1.1.2 Debye's Equations	5
1.1.3 Ionic Conductivity	7
1.2 Literature Survey	10
2 Methodology	12
2.1 Sample Preparation	12
2.2 Dielectric Measurements using DAK-TL	13
3 Results and Discussion	16
3.1 Effect of Salt Concentration on Dielectric Properties	16
3.2 Effect of Sugar Concentration on Dielectric Properties	17
3.3 Discussion and Possible Sources of Error	18
3.4 Second Trial and Troubleshooting	20
4 Conclusion	24
References	26

List of Tables

Table 1: Salt Concentrations Prepared for Retest	20
Table 2: Sugar Concentrations Prepared for Retest	21

List of Figures

Figure 1: Polarizability vs Frequency. Adapted from Dielectric Properties of Epoxy/ Al_2O_3 Nanocomposites by M. J. Kadhim et al.	3
Figure 2: Dielectric Constant and Loss of an Aqueous Ionic Solution. Adapted from Dielectrics in Electric Fields by Raju.....	8
Figure 3: Preparing Salt and Sugar Solutions at Various Concentrations	13
Figure 4: DAK-TL Set-up.....	15
Figure 5: Dielectric Constant/Loss vs. Frequency of Salt Water at Various Concentrations 200 MHz to 10 GHz.....	17
Figure 6: Conductivity vs. Frequency of Salt Water at Various Concentrations 200 MHz to 10 GHz	17
Figure 7: Dielectric Constant/Loss vs. Frequency of Sugar Water at Various Concentrations 200 MHz to 10 GHz.....	18
Figure 8: Conductivity vs. Frequency of Sugar Water at Various Concentrations 200 MHz to 10 GHz	18
Figure 9: Salt and sugar solutions with various concentrations prepared for retest	21
Figure 10: Dielectric Constant/Loss vs Frequency of 6.03M Salt Water 200 MHz to 5 GHz	22
Figure 11: Dielectric Constant vs Frequency of 80% Sugar Water 200 MHz to 5 GHz	23
Figure 12: Calibrating DAK-TL using Methanol and Cross-Validating using Distilled Water..	24

Acknowledgements

I would like to express my deepest appreciation to my supervisors Professor George Shaker and Professor Stefan Idziak for their continuous support and guidance throughout this project. Both Professor George Shaker and Professor Stefan Idziak were always inspiring me to learn as much as possible.

I'm extremely grateful to Ala Eldin Omer for helping me conduct the experiment on the DAK-TL in the microwave lab at CIARS twice.

I must also thank my parents for their unwavering support and encouragement throughout the term.

1 Introduction

Dielectrics have a large range of applications such as communication usages, antennas, and radars [1]. A particular area of increasing importance is the non-invasive real-time monitoring of food products throughout the production stages to ensure quality is maintained from raw material to finished product. One example of using the dielectric properties in the food industry is to determine the moisture content of grain [2]. According to [2], it is possible to develop an inexpensive and non-invasive radar that can be installed on a production line to determine the moisture content of grains while they are being conveyed. This idea may be possibly implemented for a wide range of food products on a conveyor belt. However, it is important to understand how the material being measured responds to an applied electromagnetic field since the dielectric properties of a material depend on both frequency and temperature as well as the material's composition, density, and particle size [2].

The purpose of this report is to examine the effect of an applied time varying electric field on the dielectric properties of various concentrations of salt and sugar dissolved in water at room temperature over the frequency range 200 MHz to 10 GHz. These are two common ingredients found in many food products. This report is split up into 3 main sections: theoretical background, methodology, and experimental results. In the theoretical background section, the physical processes behind polarization and variation of dielectric constant or loss with concentration will be examined. Measurements will be conducted using an open-ended coaxial probe system called the DAK-TL (Dielectric Assessment Kit for Thin Layers) and results will be plotted using Python.

1.1 Theoretical Background

1.1.1 Dielectrics in an Applied Electric Field

Consider a parallel plate capacitor with a linear dielectric slab consisting of polar molecules inserted between the two plates. Upon applying an electric field, the molecules will experience a torque that forces them to rotate themselves in the direction of the electric field. The electrical energy passing through the capacitor is stored in the polarized molecules. The easier the molecules are to polarize, the higher the dielectric constant. This can be seen in Equation (1) for linear dielectrics [3]

$$\vec{P} = \epsilon_0(\epsilon_r - 1)\vec{E} \quad (1)$$

where ϵ_0 is the permittivity of free space and ϵ_r is the relative permittivity. In a time-varying field, the relative permittivity will be a complex quantity and is defined as

$$\epsilon_r^* = \epsilon' - i\epsilon'' . \quad (2)$$

The real part of the relative permittivity is known as the dielectric constant which quantifies the ability of a material to store electrical energy. The imaginary part of the relative permittivity is known as the dielectric loss which describes how much energy is dissipated in a material from internal friction, heat, or other physical processes [1]. A high dielectric loss will lead to a large power loss.

It is important to note that although the real part of the relative permittivity is called the dielectric constant, the value varies with frequency. As previously mentioned, both the dielectric constant and dielectric loss are frequency dependent. This is due to the different types of polarization mechanisms being observable at certain frequencies as well as in certain materials. At zero frequency (DC), the measured dielectric constant is called the static dielectric constant.

As frequency tends towards a relatively large number, the dielectric constant will tend towards a constant value called the high frequency dielectric constant. At optical frequencies, the high frequency dielectric constant will approach the index of refraction of the material squared [3]. Both values depend on the relaxation time of a material [4].

There are four main polarization mechanisms: interfacial polarization, dipolar/orientational polarization, ionic/atomic polarization, and electronic polarization [4]. The total polarization at DC is given by

$$P_T = P_{int} + P_{dip} + P_{ion} + P_e \quad (3)$$

where P is a sum of all the dipole moments. For the purposes of this report, the interfacial polarization will not be examined. According to Figure 1 presented in [5] of the general polarizability vs frequency plot, dipolar polarization is observed until about 10^9 Hz. Likewise, ionic polarization is observed until about 10^{13} Hz. In the microwave region of the electromagnetic spectrum, only the dipolar/orientational, ionic/atomic, and electronic polarizations can be observed.

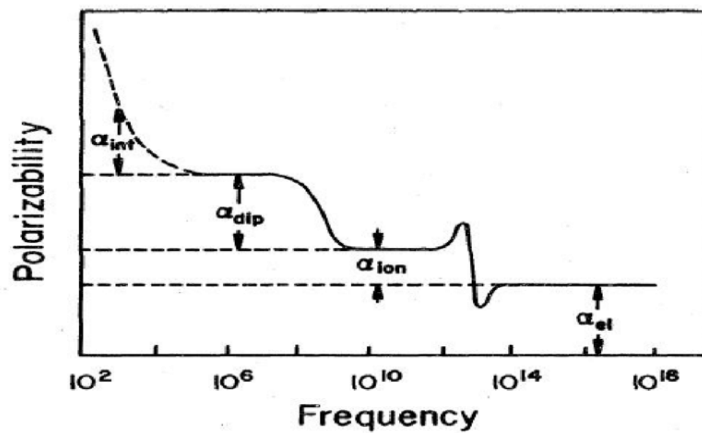


Figure 1: Polarizability vs Frequency. Adapted from Dielectric Properties of Epoxy/ Al_2O_3 Nanocomposites by M. J. Kadhim et al.

Dipolar polarization or orientational polarization is inherent to molecules with a permanent dipole such as H₂O or molecules with an induced dipole [4]. The equation for dipolar polarization given in [4] is

$$\overrightarrow{P_{dip}} = \frac{Np^2}{3kT} \vec{E}. \quad (4)$$

Examining the above equation if temperature increases, the polarization decreases, and the static dielectric constant decreases. In fact, this is the only type of polarization that shows a temperature dependence in its equation where the polarization is inversely proportional to temperature [6]. Relaxation behaviour is also prevalent in this type of polarization. When an electric field is applied, the dipoles will orient themselves in the direction of the field. The time that it takes for them to rotate from an excited state to a new equilibrium or random distribution is called the relaxation time, τ . The relaxation behaviour is an important concept that will be seen later when discussing the Debye equations. As frequency increases to about 10^9 Hz [5], the molecules cannot keep up with the rapidly oscillating field and will become nearly motionless in respect to rotations. The polarization will then no longer contribute to the total polarizability at this frequency and higher ones.

Ionic polarization applies to ionic crystals while atomic polarization occurs in polar covalent molecules [4]. Polar molecules are asymmetric [7] and have a permanent dipole [4]. Examples include salt and sugar. On the other hand, non-polar molecules such as diatomic molecules are the opposite and only exhibit electronic polarization. Electronic polarization or optical polarization is inherent to all atoms because the applied field displaces the electrons of the material [7]. Both ionic/atomic and electronic polarizations can be described by resonance behaviour [4], [6] similarly to a mass on a spring. No equation for ionic/atomic polarization is given in [4], but electronic polarization is defined as

$$\vec{P}_e = N(4\pi\epsilon_0 R^3)\vec{E}. \quad (5)$$

It is mentioned in [4] that a way to obtain the value of the ionic/atomic polarizability would be to subtract the dipolar and the electronic polarizabilities from the total polarizability.

1.1.2 Debye's Equations

In deriving the Debye Equations, ionic/atomic polarization was neglected and only the electronic and dipolar polarizations were accounted for. The derivation can be found in [4] where the polarization build-up in a dielectric from 0 to some saturated polarization when an electric field is applied is examined. An alternative derivation can be found in [7] with a similar approach, but a decay function is used instead. Regarding the derivation in [4], it was assumed that the molecules are spherical, and the dielectric behaved as a linear one. It was also assumed that an electric field of the form $E = Ae^{i\omega t}$ was applied. The resulting equations describe the behaviour of polar dielectric as a function of frequency and are defined as

$$\epsilon' = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (\omega\tau)^2} \quad (6)$$

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_\infty)\omega\tau}{1 + (\omega\tau)^2} \quad (7)$$

where ϵ_s is the static dielectric constant and ϵ_∞ is the high frequency dielectric constant.

Since the Debye equations are best used to describe relaxation behaviour found in dipolar and polar dielectrics, it will fall apart for nonpolar materials which only exhibit electronic polarization. Another aspect where the Debye equations will fall apart is when the material exhibits more than one relaxation time. Not many materials exhibit ideal Debye relaxation besides distilled water [4]. Because the Debye equations take into consideration dipolar and electronic polarizations, the model will start to break down at some high frequency. In [8], the single Debye model as introduced above is applicable for distilled water up to 50 GHz with a

temperature ranging from 0°C to 30°C. It is mentioned that at 10 GHz there is an approximate 1% error, while at 50 GHz there is an approximate 5% error between measured and theoretical data.

The static dielectric constant, high frequency dielectric constant, and the relaxation time are all dependent on the “purity” of the water being measured. That is, with any concentration of impurity in the water, the parameters will be affected. The general trend seems to be as the static dielectric constant decreases, the relaxation time increases, and the high frequency dielectric constant increases as concentration increases. These trends will be further discussed in the literature survey where various papers are examined. It is mentioned in [9] that the solute disrupts the H-bond network of water when it is dissolved, therefore the static dielectric constant decreases regardless of the type of solute. This could be due to the water molecules bonding with the solute and forming hydration shells around them. With these hydration shells, the moment of inertia of the bound molecules will increase, decreasing the mobility of the free water molecules [10].

The relaxation time depends on temperature, shape, and axis of rotation [4]. It is possible to look at relaxation time both macroscopically and microscopically. The relaxation time used in the Debye model is the macroscopic relaxation time [4]. For microscopic relaxation time, the equation given in [4] is

$$\tau_m = \frac{4\pi\eta a^3}{kT} \quad (8)$$

where η is the viscosity of the liquid and a is the molecular radius. Since there is a linear relationship between the relaxation time and viscosity, we can see that with an increase of viscosity there will be an increase in relaxation time. With an increase of concentration in a

solution, the relaxation time as well as the dielectric loss will increase because there will be greater internal friction experienced by rotating molecules.

Some notable features of the ϵ' - ω and ϵ'' - ω curves from [4] are that the maximum dielectric loss occurs at $\omega\tau = 1$ or $\omega = \frac{1}{\tau}$ and has a value of $\frac{\epsilon_s - \epsilon_\infty}{2}$. At this frequency, the dielectric constant takes on the value $\frac{\epsilon_s + \epsilon_\infty}{2}$. This frequency is called the relaxation frequency and may be denoted ω_p . With an increase of concentration in a solution, the static dielectric constant will decrease, and the high frequency dielectric constant will increase, giving the maximum dielectric loss attained a smaller value. Looking at the derivation of the Debye equations in [4], the polarization build-up and rate of change of polarization are

$$P(t) = P_\infty \left(1 - e^{-\frac{t}{\tau}}\right) \quad (9)$$

$$\frac{dP(t)}{dt} = \frac{1}{\tau} P_\infty e^{-\frac{t}{\tau}} \quad (10)$$

respectively. With an increase in relaxation time, there will be a faster polarization build-up. Likewise, there will be a slower polarization build-up with a decrease in relaxation time. The rate for the polarization to decay will be analogous to the rate of build-up. If there is an increase in concentration, there will be a quicker polarization decay, so the relaxation frequency will occur sooner.

1.1.3 Ionic Conductivity

An important consideration that needs to be accounted for aqueous ionic solutions is the fact that they are electrolytic. That is, if salt is dissolved into distilled water, the salt dissociates into ions and the solution becomes conductive. If sugar is dissolved into distilled water, the sugar

does not dissociate into ions and the solution remains non-electrolytic and no ionic conductivity occurs. Ionic conductivity arises when there are free flowing ions present in a solution. There is a Debye model for aqueous ionic solutions that has been slightly modified to account for the ionic conductivity of a solution from [14]

$$\epsilon_r^* = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 - i\omega\tau} + \frac{i\sigma}{\omega\epsilon_0} \quad (11)$$

which can be separated into real and imaginary components giving the original dielectric loss an extra term

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_\infty)\omega\tau}{1 + (\omega\tau)^2} + \frac{\sigma}{\omega\epsilon} . \quad (12)$$

The first term of the dielectric loss is the loss due to the rotation of the dipoles and the second term is the loss due to ionic conductivity [11]. The behaviour of the dielectric constant and loss of an aqueous ionic solution can be illustrated in Figure 2 presented in [4].

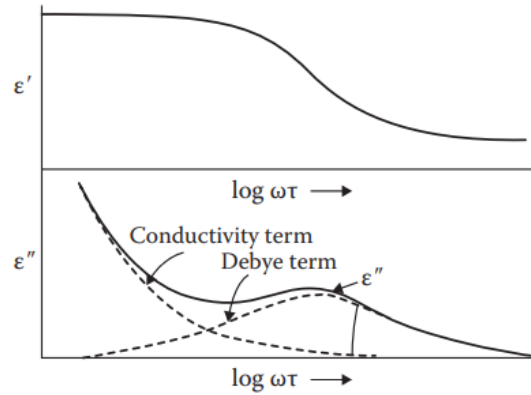


Figure 2: Dielectric Constant and Loss of an Aqueous Ionic Solution. Adapted from Dielectrics in Electric Fields by Raju

The conductivity, σ can be approximated to be equal to σ_s which arises due to the ionic conductivity of a solution at DC. In these cases, the Debye-Falkenhagen effect is assumed to be negligible. The effect describes the increase in the conductivity as frequency increases [15] and

arises due to AC currents [16]. There have been several models that have been developed to explain the Debye-Falkenhagen effect, but it has been a work in progress [17].

Mathematically, the loss due to ionic conductivity approaches zero as frequency tends towards infinity, so the term only greatly affects the dielectric loss at lower frequencies. An explanation for this phenomenon is provided by Gadani et al. [11] that seems to be describing the Debye-Huckel theory. Similar explanations are also found in [10], [17]-[18]. The Debye-Huckel theory describes the behaviour of strong electrolytes [15] such as salt dissolved in distilled water. The Debye-Huckel theory first introduced the concept of an ionic atmosphere in 1923 which has a similar idea to hydration shells [15]. The ionic atmosphere is defined as a spherical cloud of charge that describes the average distribution of ions in a region of space. Two phenomena arise from this theory called the asymmetric and the electrophoretic effects and together they lower the mobility of ions in a solution. The asymmetric effect describes the displacement of the central ion and the surrounding ionic atmosphere due to the presence of an applied electric field [15]. On the other hand, the electrophoretic effect describes the retardation force that is exerted on the central ion as it moves in the opposite direction of the ionic atmosphere [15]. There will always be a delay or lag of the ionic atmosphere as it tries to return to its equilibrium position.

As frequency increases, the asymmetric effect is reduced, and the central ion oscillates more quickly than at a lower frequency [10], [14]. The central ion eventually becomes motionless at some high frequency and the loss due to ionic conductivity term becomes negligible. In [4], it is mentioned that the conductivity of the solution does not decrease and only the loss due to ionic conductivity decreases. Interestingly, as frequency increases, the dielectric constant decreases, and the conductivity increases [4], [19]. Murphy and Morgan [19] mentioned that the increase in

conductivity with frequency may be due to fewer restoring forces acting on the ions. Chandra and Bagchi [17] reported a similar idea, but about the Debye-Falkenhagen effect instead. Perhaps understanding this process will be important in understanding the variation of the high frequency dielectric constant with concentration. For the purposes of this report, only ionic conductivity is examined since the DAK-TL 3.5 probe is only capable of measuring materials from 200 MHz to 20 GHz.

1.2 Literature Survey

Salt water is commonly studied to develop radiometers for remote sensing of seawater [20]-[21]. It is also commonly studied to monitor water quality for agricultural activity [10]. To develop an accurate model for salt water, frequency, temperature, and salinity will need to be accounted for [20]. Stogryn [20] used regression methods to derive an accurate model for salt water at microwave frequencies. Unfortunately, due to the local interaction between molecules it is difficult to derive a physical model without regressions. Xu Yuan et al. [22] attempted to derive a physical model for saltwater at radio frequencies but achieved satisfactory results.

Another model based on Stogryn's regression models is the Klein and Swift model [21]. The main difference between the two models is that Stogryn's model is dependent on normality and a separate equation for normality based on salinity is given, while the Klein and Swift model only requires salinity [14]. Gadani et al. [14] compared the Stogryn and Klein and Swift models and determined that both model the dielectric loss of salt water well. However, the Stogryn model is better at modelling the dielectric constant above 0.9 GHz while the Klein and Swift model is better below 0.9 GHz. It is also reported in [14] that over the tested frequency range 200 MHz to 1.4 GHz that the dielectric constant decreases as salinity increases, and the dielectric loss of pure water increases as frequency increases, while the dielectric loss of saline water decreases as

frequency increases. The decrease of dielectric loss of saline water can be modelled by the aqueous ionic Debye equation provided in section 1.3 and is explained due to the ionic conductivity of the solution. It can be noted that the conductivity increases as the concentration of salt increases in the solution.

An interesting comparison between salt water and sugar water is made by Cheng et al. [18]. Concentrations of 5-25% salt in water and concentrations of 5-80% sugar, both in increments of 5%, are prepared and tested over the frequency range 200 MHz to 20 GHz. It is mentioned that the reason why 25% is the highest concentration of salt used is because the solution will become saturated by that concentration. Any extra salt added to the solution will give similar results. It appears that sugar water becomes saturated with a higher concentration of sugar than sugar. It can be seen in the graphs of dielectric loss vs frequency of various sugar concentrations in [18] that the maximum dielectric loss decreases with an increase in concentration. The occurrence of the peak also happens at an earlier relaxation frequency with the concentration of sugar increases. The conclusion of [18] is that an increase in the concentration of salt or sugar will lower the dielectric constant and increase the dielectric loss.

The variability of glucose concentrations in ionic aqueous solutions have been tested in [11]-[12]. Omer [11] tested artificial blood with different glucose concentrations samples over the frequency range 300 MHz to 67 GHz using the DAK-TL and reported a distinct increase in the dielectric constant with concentration at the higher frequency range. Cano-Garcia [12] tested saline solutions with different glucose samples over the frequency range 47 GHz to 67 GHz and reported the dielectric constant increases with concentration at the millimetre frequency range. Interestingly, the fitted Debye model in Omer's work shows an increase in the static dielectric constant with concentration while the fitted Debye model in [12] shows a decrease in the static

dielectric constant with concentration, which agrees with the present theory. Both papers fitted the high frequency experimental data to a single pole Debye model. In [13], aqueous solutions of D-glucose and D-fructose were tested over the frequency range 300 KHz to 40 GHz. Fuchs [13] reported that with an increase of concentration, the static dielectric constant decreased, relaxation time increased, and the high frequency dielectric constant increased for both D-glucose and D-fructose.

2 Methodology

2.1 Sample Preparation

Initial samples of 2%, 4%, 6%, 8%, and 10% of salt or sugar were prepared using an Ozeri Pronto Digital Multifunction and Food Scale that measured with accuracy up to 1 gram. Subsequent measurements of salt and sugar solutions were prepared with higher accuracy outlined later. Windsor Iodized Table Salt and Redpath Special Fine Granulated Sugar were dissolved separately into Equate Distilled Water. To prepare a 2% solution, 1 gram of either salt or sugar was measured into a sample bottle. The bottle was then filled with distilled water until the scale read 50 grams. This procedure was repeated for the remaining concentrations of salt and again for sugar. The samples were then swirled until the solute was dissolved and sat at room temperature for 20-22 hours before testing. The weight of a sample bottle would vary between 89-91 grams and a cap weighed about 3 grams.



Figure 3: Preparing Salt and Sugar Solutions at Various Concentrations

Since the kitchen scale had accuracy up to 1 gram, the uncertainty per measurement would be ± 1 gram. In other words, if the scale read 1 gram of salt, the true value could be between 0-2 grams of salt. The uncertainty in the solutions was about $\pm 2\%$. This $\pm 2\%$ is the possible variation in concentration from the intended or desired concentration, i.e., the true concentration of salt of the 2% salt solution could range from 0-4%. However, it was ensured that a higher concentration salt or sugar solution would contain more salt or sugar. For example, the 4% salt and sugar solutions contained $\frac{1}{4}$ teaspoon more salt or sugar compared to the 2% salt or sugar solution.

2.2 Dielectric Measurements using DAK-TL

The Dielectric Assessment Kit for Thin Layers (DAK-TL) is a device that can measure the dielectric constant, dielectric loss, conductivity, and loss tangent of solids and liquids. It uses an open-ended coaxial probe technique and calculates the S11 parameter, or reflectance coefficient, of the sample [2], [10]. The DAK software then uses this measured parameter to calculate the dielectric properties. The system was connected to a Keysight PNA Network Analyzer N5227A.

There are two possible probes for measurements over different frequency ranges: the DAK-TL 3.5 probe (200 MHz – 20 GHz) and the DAK-TL 1.2 E (5 GHz – 67 GHz) probe.

Although the DAK-TL 3.5 probe has the capability of making measurements over the range 200 MHz to 20 GHz, the system was calibrated over the frequency range of 200 MHz to 10 GHz with a resolution of 50 MHz. Measurements are most accurate over a smaller range of frequencies; therefore 10 GHz was selected instead of 20 GHz to ensure a higher accuracy of measured data.

An Open-Short-Load (OSL) calibration method was used to calibrate the DAK-TL. Air was measured for the open technique, copper tape was used for the short technique, and about 9 mL of Equate distilled water was used for the load. Distilled water was then measured three times and exported to an Excel file with the target data of distilled water at 20° C provided by the DAK software. There was an approximately 90% agreement with the measured distilled water data to the reference data of distilled water at 20° Celsius. The set-up of the DAK-TL is shown in Figure 2. The plot shown leftmost on the computer screen displays the dielectric constant and the dielectric loss of distilled water, where the red lines are the reference data stored in the DAK software and the white lines are the measured distilled water data. The middle plot displays the deviation of the white lines (measured data) to the red lines (reference data).

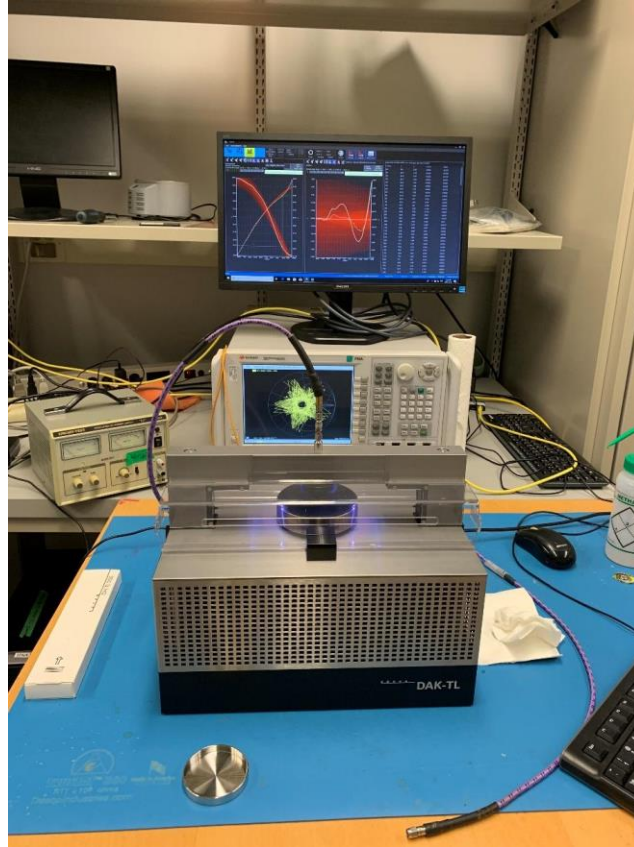


Figure 4: DAK-TL Set-up

A syringe was used to draw out 9 mL of each sample into the metal petri-dish provided. The petri-dish was placed underneath the open-ended probe and three measurements were taken for each sample. The probe was lifted and placed back into the solution for each trial to minimize air bubbles under the probe and to ensure repeatability among the trials. After completing the measurements for a sample, the sample was discarded, and the metal petri-dish was thoroughly cleaned with sanitizer. The process was repeated for distilled water, 2%, 4%, 6%, 8%, and 10% salt and sugar solutions.

3 Results and Discussion

3.1 Effect of Salt Concentration on Dielectric Properties

The dielectric constant and loss vs frequency of distilled water and salt concentrations are plotted in Figure 5. There is a noticeable increase in the dielectric constant with frequency from 200 MHz to about 3 GHz. The plot of the dielectric constant does not seem to agree well with the papers discussed in the literature survey regarding salt water. Even with a concentration of 10% salt in water, the DAK-TL machine does not differentiate between distilled water and salt water well. According to [10], [18], [20]-[21] there should be a more noticeable difference than what is shown in Figure 5. The plot also does not show any losses due to ionic conductivity for some reason. The value of the dielectric loss is shown to be decreasing with an increase in concentration. This does not align with the results for salt water from [10], [18], [20]-[21]. In fact, the results given by the DAK-TL were the opposite of what should have been expected.

Although no reference data has been provided for the conductivity vs frequency of salt water, Figure 6, in the resources consulted thus far, it is odd that the value of the conductivity decreases with an increase in concentration. When salt dissociates into distilled water, ionic conductivity arises at DC, but the plot strangely shows that the static conductivity starts at about zero. From general physics knowledge, the conductivity of a saline solution should increase with an increase in salinity.

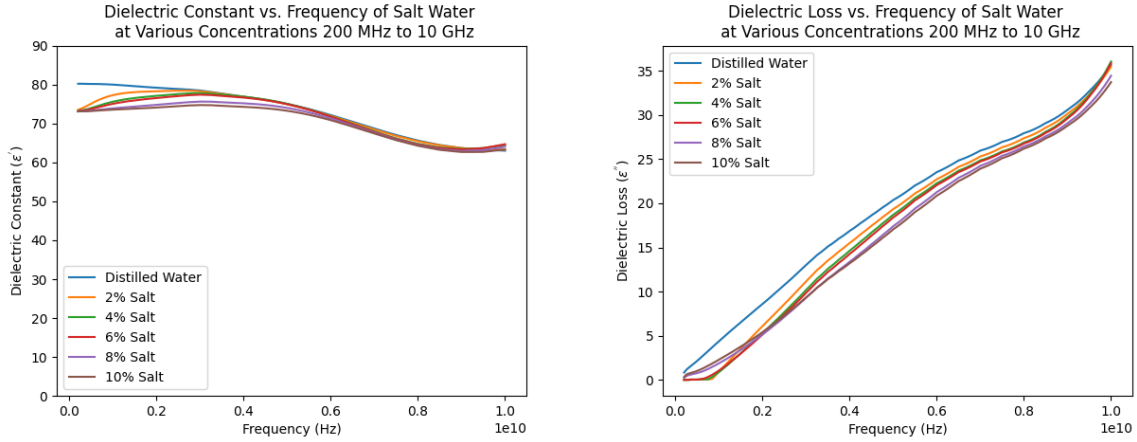


Figure 5: Dielectric Constant/Loss vs. Frequency of Salt Water at Various Concentrations 200 MHz to 10 GHz

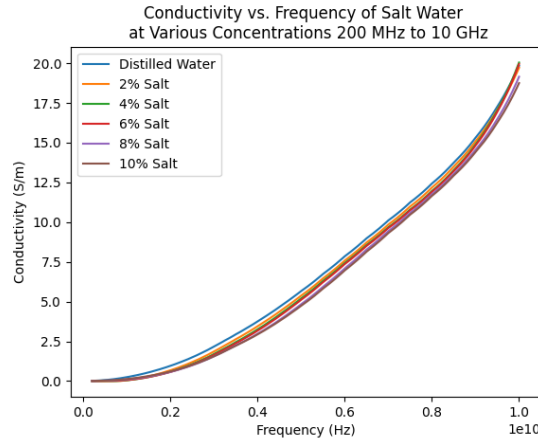


Figure 6: Conductivity vs. Frequency of Salt Water at Various Concentrations 200 MHz to 10 GHz

3.2 Effect of Sugar Concentration on Dielectric Properties

The dielectric constant and loss vs frequency of distilled water and sugar water is shown in Figure 7. The conductivity vs frequency of distilled water and sugar water are shown in Figure 8. From the experimental results in [18], the decrease in value of the dielectric constant should be slower than that of salt in water. A higher concentration of sugar would be required to lower the value of the dielectric constant to the same amount as 5% salt or another concentration of salt. The dielectric constants of sugar water at low concentrations should not deviate much from water but should still decrease the value of the dielectric constant over the frequency range

of 200 MHz to 10 GHz. Unfortunately, zooming in onto the plot in Figure 6, the value of the dielectric constant appears to be increasing with an increase in concentration. Similarly, to the dielectric loss result of salt water, the value of the dielectric loss of sugar water appears to be decreasing with an increase in concentration. These results do not align with the results in [12]-[13], [18] and is the opposite of what is expected for some reason.

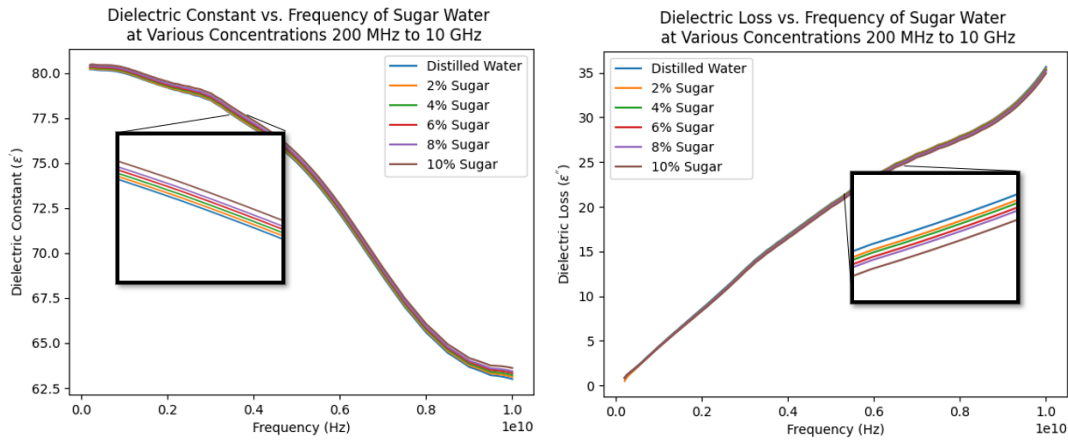


Figure 7: Dielectric Constant/Loss vs. Frequency of Sugar Water at Various Concentrations 200 MHz to 10 GHz

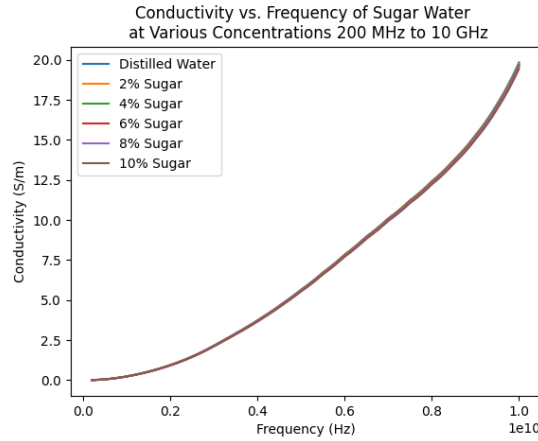


Figure 8: Conductivity vs. Frequency of Sugar Water at Various Concentrations 200 MHz to 10 GHz

3.3 Discussion and Possible Sources of Error

The cause for the DAK-TL 3.5 measurements being nearly opposite of what is expected from [10], [18], [20], and [21] is unclear. One could argue that the method of sample preparation

could introduce a great deal of uncertainty into the data, or perhaps the machine is not accurate with low concentrations of salt or sugar water. However, comparing only the distilled water and 10% concentrated solutions, which the concentration is not that low, there should still be a noticeable decrease in the value of the dielectric constant or an increase in the value of the dielectric loss. The sample jars used were not watertight and were left at room temperature for about a day. It is possible that evaporation and crystallization could have affected the concentration of the solution, but it should not be enough to give drastically opposite results of what should have been expected.

Another possible error source could have been air bubbles that were under the probe and not visible when testing. Each of the measurements was completed 3 times by lifting and placing the probe in the solution to minimize air bubbles, but it is possible that trapped air bubbles could have influenced the measured results. Though, if this were the case, it is incredibly strange how it influenced all the measurements when there were 10 samples in total, 5 samples for salt and 5 samples for sugar as well as being present in each of the three trials conducted per sample.

It is reported in [2] that the open-ended coaxial probe technique may be inaccurate for very low frequencies and low dielectric constants or losses. The open-ended coaxial probe technique has been a common choice for performing measurements on solutions especially over the frequency range 200 MHz to 20 GHz and is relatively simple to use. This technique was used in [10], [11], [14], and [18]. Omer [11] used the DAK-TL to measure the dielectric constants and losses of artificial blood samples with varying glucose concentrations and reported that it was difficult to determine the trend over the frequency range 300 MHz to 10 GHz. However, the high frequency experimental data fitted to the single pole Debye model shows an increase in dielectric constant with concentration, which is the opposite of what was reported in [12].

Perhaps this was an algorithmic error in the fitting technique, or possibly a more serious error in the machine.

According to the DAK-TL manual [23], it is recommended to calibrate the machine with one solution and cross-validate the measured readings with another solution. For example, calibrating the machine during the load step with distilled water and measuring another solution for reference comparison before testing. This solution could be 0.1M salt, methanol, etc. For the performed experiment, the machine was only calibrated using distilled water and cross-validation was not checked for. Perhaps the results were influenced by the miscalibration of the DAK-TL.

3.4 Second Trial and Troubleshooting

New samples were prepared to conduct a retest using the DAK-TL with a wider range of concentrations of both salt and sugar listed in Tables 1 and 2 respectively. Samples were measured using a Sartorius BP 2100 S scale with accuracy up to a hundredth of a gram. The uncertainty per measurement was approximately $\pm 0.02\text{g}$. Samples were stored in plastic watertight Qorpak containers and sealed with Parafilm M as shown in Figure 9 to prevent evaporation from occurring. Before testing, samples were shaken well. The same procedure for calibration as outlined in section 2.2 was used, but the frequency range 200 MHz to 5 GHz was chosen instead. With a smaller frequency range, improved accuracy in the results were hoped to be achieved.

Table 1: Salt Concentrations Prepared for Retest

Salt			
Concentration	Molarity (mol/L)	Weight (g)	Weight of Distilled Water (g)
0.58%	0.100	0.29	50.00
2%	0.342	1.00	50.01
4%	0.684	2.00	50.01
6%	1.027	3.00	50.00
8%	1.369	4.00	50.00

10%	1.711	5.00	50.01
12%	2.070	6.05	50.01
20%	3.450	10.08	50.00
35%	6.030	17.62	50.01

Table 2: Sugar Concentrations Prepared for Retest

Sugar		
Concentration	Weight (g)	Weight of Distilled Water (g)
2%	1.00	50.00
4%	2.00	50.01
6%	3.00	50.01
8%	4.00	50.01
10%	5.00	50.01
20%	10.00	50.01
40%	20.00	50.00
60%	30.00	50.00
80%	40.00	50.00



Figure 9: Salt and sugar solutions with various concentrations prepared for retest

Unfortunately, due to time constraints and limited lab access, only the highest concentrations of salt and sugar were tested. This was to determine whether the trends observed from the previous measurements were still prevalent. If results showed the same behaviour at high concentration, the sample preparation may not be the issue and the possibility of the machine being inaccurate at low measurements may be ruled out. Uncertainty was minimized where possible and the salt and sugar samples tested were tested several times instead of 3. After

measurements of the high concentrated solutions, the machine was recalibrated several times with the open short load technique with distilled water and the solutions were then tested again. This process was repeated several times. The calibration with distilled water showed an average of 99% accuracy to the target water data provided by the DAK system.

The results for the 6.03M salt solution are shown in Figure 10. The dielectric constant does not increase before 3 GHz and there is more differentiability in the salt solution from distilled water than in Figure 3. This concentration of salt was selected to repeat the measured results for 6.03M salt found in [10]. Although there is more differentiability than previously, the dielectric constant still does not read as low as it should. The dielectric loss appears to be decreasing with an increase in concentration and the loss due to ionic conductivity is still missing. The trend for conductivity was the same as in Figure 5 where the conductivity of 6.03M salt water was lower than distilled water.

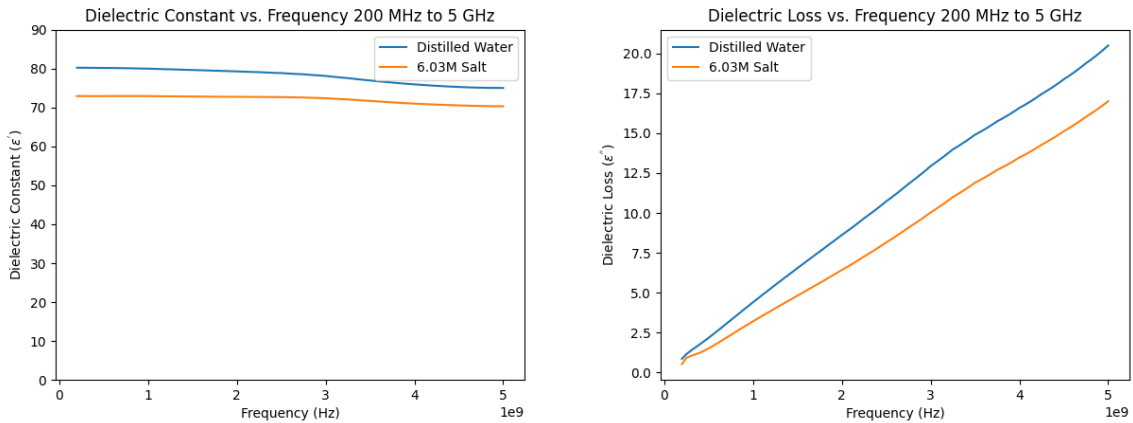


Figure 10: Dielectric Constant/Loss vs Frequency of 6.03M Salt Water 200 MHz to 5 GHz

The results for 80% sugar are shown in Figure 11. Comparing these results to Figure 7, the results did not improve with the retest and are still showing the same trends. The value of the dielectric constant of 80% is shown to be higher than the value of the dielectric constant of distilled water while the dielectric loss is less than distilled water. The concentration of sugar

selected was chosen to repeat the measured results for 80% sugar in [18], but the retest showed unsatisfactory results.

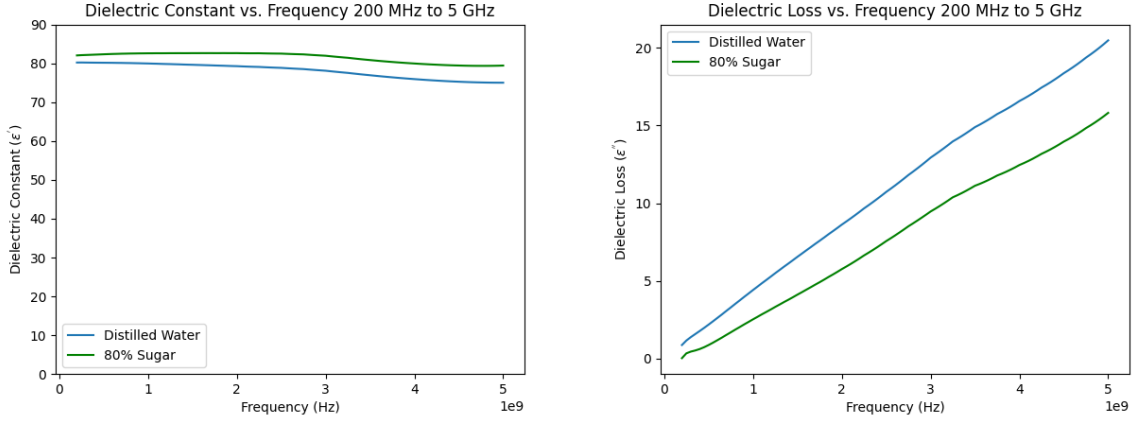


Figure 11: Dielectric Constant vs Frequency of 80% Sugar Water 200 MHz to 5 GHz

Next, to determine whether the machine was faulty, methanol was measured, and its dielectric constant and loss were compared to those of distilled water. Strangely, the machine was unable to differentiate between methanol and distilled water and showed that methanol and distilled water had the exact same dielectric constant and dielectric loss. This would normally be impossible, since the dielectric constant of methanol should be much lower than distilled water while the dielectric loss would be greater over this frequency range. Bao et al. [24] conducted a study on mixtures of water-methanol and water-ethanol solutions. They showed measured results of both water-alcohol solutions with varying volume fraction of water from 0% to 100% in increments of 10%. At 0% water, the solution would be purely methanol or ethanol. There is a large difference in the dielectric constant between the pure alcohol solutions and distilled water, the alcohol solutions being lower.

The machine was recalibrated using the open short method again but used methanol as the load. Distilled water was measured to compare the dielectric constant and loss to the methanol calibration. The result of this calibration is shown in Figure 12 and showed very little

to no success. For some reason, the dielectric constant of distilled water read a little higher than the dielectric constant of methanol. As seen in [24], this cannot be possible. Testing the methanol and distilled water using the DAK-TL 1.2 E for troubleshooting purposes over the frequency range 50 GHz to 67 GHz, the machine was not able to differentiate between the two solutions.

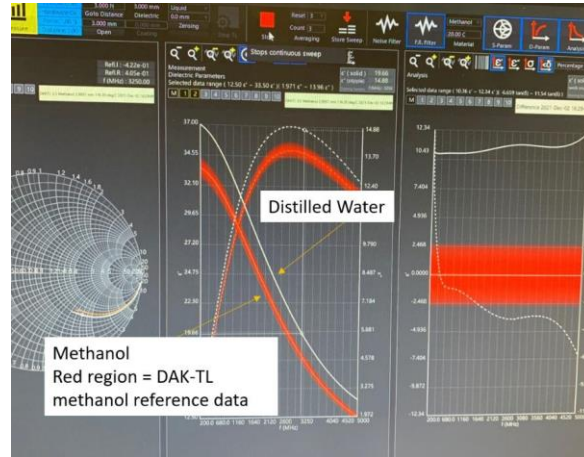


Figure 12: Calibrating DAK-TL using Methanol and Cross-Validating using Distilled Water

The fitted static dielectric constant parameter that increased with concentration obtained by Omer [11] for different glucose concentrations in artificial blood samples may have arisen from the DAK-TL. Further troubleshooting with the machine will be required on both the DAK-TL 3.5 and 1.2 E probes, and perhaps a full calibration with several materials will be necessary.

4 Conclusion

The dielectric properties of 2%-10% salt and sugar solutions at room temperature were measured over the frequency range of 200 MHz to 10 GHz using the DAK-TL 3.5 probe. Comparing the results obtained to those in previous works were inconsistent and further troubleshooting with the DAK-TL will be required. According to the literature survey conducted, the increase of salt or sugar in a solution should decrease the value of the dielectric

constant and increase the value of the dielectric loss relative to distilled water. The results obtained showed drastically different values from what should have been expected. A possible way to further this study could be to test different types of salt or sugar, such as non-iodized salt and raw sugar, to determine their effect on their dielectric properties or testing the same salt and sugar solutions used in this project at a higher frequency range. The study can be further applied by examining varying concentrations of nonpolar constituents in distilled water. Studying the composition of food products and their effects on the dielectric properties will be essential in developing an accurate and non-invasive radar for food monitoring.

References

- [1] R. G. Geyer, “*Dielectric Characterization and Reference Materials*, ” Washington, D.C.: U.S. Dept. of Commerce, 1990.
- [2] M.S. Venkatesh and V. Raghavan, “An Overview of Dielectric Properties Measuring Techniques”, *Can. Biosystems Eng. / Le Genie des biosystems au Canada*, vol. 47, pp. 15-30, 2005.
- [3] D. J. Griffiths, *Introduction to Electrodynamics*, 4th Edition. Pearson Educ., Inc., 2013.
- [4] G. G. Raju, *Dielectrics in Electric Fields*, 2nd Edition. Taylor & Francis Group, Boca Raton, FL, USA, 2017.
- [5] A. Qasim, “Mechanical Properties of Epoxy/Al₂O₃ Nanocomposites”, 2018.
- [6] J. D. Jackson, *Classical Electrodynamics*, 3rd Edition. John Wiley & Sons, Inc., August 1998.
- [7] H. Frohlich, *Theory of Dielectrics: Dielectric Constant and Dielectric Loss*, 2nd Edition. Clarendon Press, 1987.
- [8] F. T. Ulaby and D. G. Long, *Microwave Radar and Radiometric Remote Sensing*. Univ. of Michigan Press, Ann Arbor, MI, USA, 2014.
- [9] D. C. Elton, “Understanding the dielectric properties of water,” Ph.D. dissertation, Dept. Phys., Stony Brook Univ., Stony Brook, NY, USA, December 2016.
- [10] C. Meng, “REFLECTION AND DIELECTRIC MEASUREMENT FOR SALINITY OF WATER USING MICROSTRIP LOOP ANTENNA AND DIELECTRIC PROBE,” *Int. J. of GEOMATE*, 2016.
- [11] A. E. Omer, S. Gigoyan, G. Shaker and S. Safavi-Naeini, "WGM-Based Sensing of Characterized Glucose- Aqueous Solutions at mm-Waves," in *IEEE Access*, vol. 8, pp. 38809-38825, 2020, doi: 10.1109/ACCESS.2020.2975805.
- [12] H. Cano-Garcia et al., “Detection of glucose variability in saline solutions from transmission and reflection measurements using V-band waveguides,” *Measurement Science and Technology*, vol. 26, 2015.
- [13] K. Fuchs and U. Kaatz, “Molecular Dynamics of Carbohydrate Aqueous Solutions. Dielectric Relaxation as a Function of Glucose and Fructose Concentration,” *J. Phys. Chem.*, vol. 105, pp. 2036-2042, 2001.
- [14] D. Gadani et al., “Effect of salinity on the dielectric properties of water,” *Indian J. of Pure and Appl. Phys.*, vol. 50, pp. 405-410, 2012.
- [15] V.S. Bagotsky, *Fundamentals of Electrochemistry*, 2nd Edition. John Wiley & Sons, Inc., Hoboken, NJ, USA, 2006.
- [16] J.E. Anderson, “The Debye-Falkenhagen effect: experimental fact or fiction?,” *J. of Non-Crystalline Solids*, vol. 172-174, pp. 1190-1194, 1994.
- [17] A. Chandra and B. Bagchi, “Frequency dependence of ionic conductivity of electrolyte solutions,” *Chin. J. of Chem. Phys.*, vol. 112, 2000.

- [18] C. Meng et al., "Development of Low Cost Microwave Detection System for Salinity and Sugar Detection," *Int. J. of Mechanical and Mechatronics Eng.*, vol. 14, 2014.
- [19] E. J. Murphy and S. O. Morgan, "The Dielectric Properties of Insulating Materials, III Alternating and Direct Current Conductivity," *Bell Syst. Tech. J.*, vol. 18, pp. 502-537, 1939.
- [20] A. Stogryn, "Equations for Calculating the Dielectric Constant of Saline Water (Correspondence)," in *IEEE Trans. on Microwave Theory and Techniques*, vol. 19, no. 8, pp. 733-736, Aug. 1971, doi: 10.1109/TMTT.1971.1127617.
- [21] L. Klein and C. Swift, "An improved model for the dielectric constant of sea water at microwave frequencies," in *IEEE Trans. on Antennas and Propagation*, vol. 25, no. 1, pp. 104-111, January 1977, doi: 10.1109/TAP.1977.1141539.
- [22] X. Yuan et al., "The Physical Model of Dielectric Function and Radiofrequency for NaCl Solution and Application of the Seawater," in *5th Int. Conf. on Appl. Electrostatics*, Shanghai, Nov. 2-5 2004.
- [23] *Dielectric Assessment Kit V2.4 Professional Handbook*, Schmid & Partner Engineering AG, 2018.
- [24] J.Z. Bao, "Microwave dielectric characterization of binary mixtures of water, methanol, and ethanol," *J. Chem. Phys.*, vol. 104, 1996.