USE OF MICROWAVE DIELECTRIC SPECTROSCOPY MEASUREMENTS FOR MOISTURE PREDICTION IN VIDALIA ONIONS

by

MURAT SEAN MCKEOWN

(Under the Direction of Ernest William Tollner)

ABSTRACT

Microwave Sensing offers an opportunity to nondestructively determine the amount of moisture in materials by sensing the dielectric properties of the material. In this study, dielectric properties of Vidalia onions were analyzed for moisture dependence between 6% and 92% moisture content, temperature dependence between 0 °C and 45 °C, and frequency dependence, between 200 MHz and 20 GHz. Dielectric constant at higher measured frequencies was linearly correlated with moisture content over the entire moisture range. Dielectric constant and loss factor were both directly and inversely related to temperature depending on frequency and moisture content. Use of a density-independent function that incorporates both the dielectric constant and loss factor enabled prediction of moisture content with extremely high accuracy up to 40% moisture content. The same function was utilized in development of temperature-compensated moisture prediction equations between 6% and 18% moisture content.

INDEX WORDS: Dielectric Properties, Microwave, Spectroscopy, Density-Independent, Moisture, Vidalia Onion, Permittivity

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DEDICATION

This thesis is dedicated to my family for providing loving support and motivation.

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

Vidalia Onions are a variety of sweet onions (*Allium cepa* L.) defined by Georgia and Federal Law (USDA 1989) as grown in a region of southeast Georgia. Specifically, Vidalia onions are of the Granex yellow onion variety. Based on a survey of Georgia county extension agents, the 2009 Vidalia onion crop was valued at $126,107,748 (UGA 2010). First discovered in 1931 by a man in Toombs County, Vidalia onions command a premium price at the market because of their low pungency and characteristic sweetness. This unique sweetness is due to the low sulfur concentration in the soil of the region. This also presents a drawback, as many of the pungency-creating compounds are also natural inhibitors of disease. For many years, Vidalia onions were only available from late April to mid-July. In 1990, controlled atmosphere (CA) storage technology was adapted from apple production, and now Vidalia Onions are available until the end of December (Clemens 2002).

Prior to being stored, Vidalia onions must undergo curing. This is an essential step that seals the moist regions in the interior of the onion from the outside environment, forming a barrier to the intrusion of diseases during post-harvest storage and shipping. Specifically, curing cauterizes incisions that may exist in the outer ring, drying the outer skin, and sealing the neck and roots. This process can be performed either naturally, artificially, or by a combination of both. Natural curing is performed by windrowing the harvested onions in the field and allowing sunshine to cure them. The obvious drawback to this technique is the unpredictable nature of weather. Artificial curing involves passing heated forced air over the onions that are vertically stacked in crates. This method is considered more dependable than natural curing and can ensure a more complete curing of the onion (Maw et al. 1997).

It should be noted, however, that curing, unlike standard drying, only targets the outermost layers of the product. Any loss of moisture in the interior is undesirable as Vidalia onions are sold on a weight basis. Optimally, the curing process should not remove more moisture than necessary to create a seal from the outside environment. Currently, this process is controlled simply by time and human visual inspection (Maw et al. 2004). However, varietal and year-to-year differences can require fine tuning of the curing procedure. If a method of sensing the curing of the onion skin could be developed, it would make the curing process more efficient.

In this research, microwave sensing technology has been investigated to determine whether it is feasible for use in monitoring the curing process or, in effect, the amount of moisture in the skin of the Vidalia onion. Specifically, an open-ended coaxial-line dielectric probe was used for sensing the dielectric properties of minced onions at frequencies between 200 MHz and 20 GHz at different moisture contents and temperatures. From these measurements a model for predicting moisture content was developed by using a previously documented density-independent function of the dielectric properties. This model was shown to predict moisture content with a high level of accuracy.

This research is presented in this thesis in a manuscript style with two submitted journal articles forming the core. The title of the first article is “Dielectric Spectroscopy Measurements for Moisture Prediction in Vidalia Onions,” and the second is “Dielectric Spectroscopy for Temperature-Corrected Moisture Prediction in Vidalia Onions.”

CHAPTER 2

LITERATURE REVIEW

Curing of Vidalia Onions

Curing, as previously stated, occurs whenever moisture is being removed from the surface of the onion. Natural curing is performed by windrowing the Vidalia onions in the fields after field crews have trimmed the tops and roots with clippers as shown in Figure 2.1. Ideal weather conditions for natural curing are windy with lots of sunshine; however, because of the unpredictable nature of weather, most farmers must make provisions for artificial curing (Boyette et al. 1992).

Oftentimes, artificial curing, the more costly method, is used to supplement cheaper natural curing. Artificial curing is performed by passing air heated to 40 °C through a pallet of onions at a static pressure of 0.75 in. (1.91cm). Air temperature must be strictly controlled as temperatures greater than 46 °C can damage the onions (Maw et al. 1997). Onions are considered cured once the neck region is dry and lifeless up to two layers, and any minor cuts have been sufficiently dried to the extent that there is no visible moist tissue. Over curing must be guarded against as it can result in excess moisture loss which reduces the product value (Maw and Mullinix 2005).

Figure 2.1 Natural curing of Vidalia onions by windrowing them in field.

Typically, peanut drying wagons are used for the curing process, since the Vidalia harvest season begins months after the last peanut harvest. Heated air is passed through a plenum underneath stacked onions and is allowed to rise upwards for 48 to 72 hours (Smittle and Williamson 1978). However, this solution is not the most efficient from an energy standpoint as this does not allow for the recirculation of heated air. Another solution is to use onions held in pallet boxes that can be dried in tobacco barns. In this arrangement, air is recirculated with a wet-bulb temperature of 29 °C to 32 °C and a dry bulb temperature of 38 °C. Overall weight losses from curing typically amount to 5% to 8% (Boyette et al. 1992). A photograph showing onions loaded onto pallets for drying is shown in Figure 2.2.

Figure 2.2 Vidalia Onions loaded on pallets for drying

Huge losses can occur during storage of Vidalia onions because of various diseases, particularly Botrytis neck rot (*Botrytis alli*) as shown in Figure 2.3. This disease is even of more concern with the widespread adoption of CA storage (Boyhan and Torrance 2002). This disease generally does not attack actively growing plants as it has difficulty penetrating the dry outer scale of the onion. The spores of this mold are carried by wind and enter the bulb of the onions through the cut surfaces when the tops of the Vidalia onions are removed (Walker 1919). It can remain undetected until the onions are removed from CA storage. By this time, its effects have the potential to spread throughout the entire batch and potentially render all its contents unsalable. In some years this has cost growers more than 50% to 70% of the crop (Lacy and Lorbeer 1995).

Figure 2.3 Two types of rotting common to Onions (CropIPM 2009).

Nondestructive Sensing Techniques

Currently there are no established methods for sensing the degree of curing of Vidalia Onions. The extent of sensors available for onions in general is for detection of diseased onions. Many nondestructive methods have been investigated for detection of diseased onions. These include near-infrared spectroscopy, magnetic resonance imaging, and X-rays (Upchurch et al. 1993).

A near-infrared spectrophotometer was used to measure dry matter content of onions (Birth et al. 1985). Transmittance of signal was recorded for a spectral region from 700 nm to 1000 nm. After post processing was applied; an equation was developed to predict dry-matter content of onions. Field testing of the experimental instrument showed good repeatability and stability (Birth et al. 1985).

A hyperspectral imaging technique was used to detect sour skin rot in onions. This would be used to prevent contaminated onions from being stored with good onions and potentially ruining the entire batch. Transmittance tested showed that three layers of onion tissue could be penetrated by the light source. Reflectance tests showed that sour skin infected regions could be differentiated than healthy flesh regions with the best contrast in the spectral region of 1200-1300 nm. Contrast was also found between Vidalia sweet onion surface dry layers and inner fresh layers in the spectral region of 1400-1500 nm (Wang et al. 2011). In hyperspectral imaging, the elliptical shape of onions can present problems arising from the uneven reflection at the surface. Correction factors for the elliptical shape of the onion have been developed to compensate for this (Wang and Li 2011).

X-ray inspection is a viable technique for identification of poor quality onions. Some success was achieved in detection of internal sprouting and ring separation due to microbial rot in onions by using an X-ray linescan (Tollner et al. 1995). Studies have shown that X-ray inspection combined with image processing can detect most diseases well before disease progression caused enough damage to warrant removal based on human visual inspection (Tollner et al. 2005). A simulation of the adoption of X-ray sensors into a packinghouse showed potential for significant cost savings (Mosqueda et al. 2009). This technique has not been investigated for curing detection. However, a drawback to this technique is the potential for consumer fear about irradiation of food.

Dielectric Properties

Microwave moisture sensing technology is a very mature technology in sensing moisture contents in the lower moisture range (2%-15%). This is accomplished by sensing the dielectric properties of the materials in question. Dielectric properties are the fundamental properties that determine material interaction with electric fields. They are expressed in terms of the relative complex permittivity, ε

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{1.1}$$

here the real part ε' is defined as the dielectric constant and represents the electric energy stored by the material relative to a vacuum, which is valued at 1. The imaginary part ε'' is the loss factor that represents the energy lost in the material, and j is the imaginary unit, $j = \sqrt{-1}$. In general, dielectric properties are dependent on frequency, temperature, and composition of the material. The permittivity is influenced by many different mechanisms dependent on the material and the frequency of measurement. Generally there are five different loss mechanisms that can contribute to the ε'' value. All these mechanisms can contribute to the loss factor simultaneously, so the definition of the loss factor can be written as follows (Kraszewski 1996):

$$\varepsilon'' = \varepsilon''_d(\omega) + \varepsilon''_e(\omega) + \varepsilon''_a(\omega) + \varepsilon''_i(\omega) + \varepsilon''_c(\omega) \tag{1.2}$$

where the angular frequency is $\omega = 2\pi f$, and the subscripts d, e, a, i , denote the dipolar, electronic, atomic, and interfacial polarizations respectively, and the subscript c denotes the ionic conductivity defined as:

$$\varepsilon_c''(\omega) = \frac{\sigma}{2\pi f \epsilon_0} \tag{1.3}$$

where σ is the conductivity (S/m), f is the frequency, and the permittivity of free space $\epsilon_0 = 8.854 \times 10^{-12}$ (F/m).

For the frequency range used in this study, electronic, atomic and interfacial polarizations have no significant effects, which results in the dependence of ε''being solely a function of dipolar polarizations and ionic conductivity:

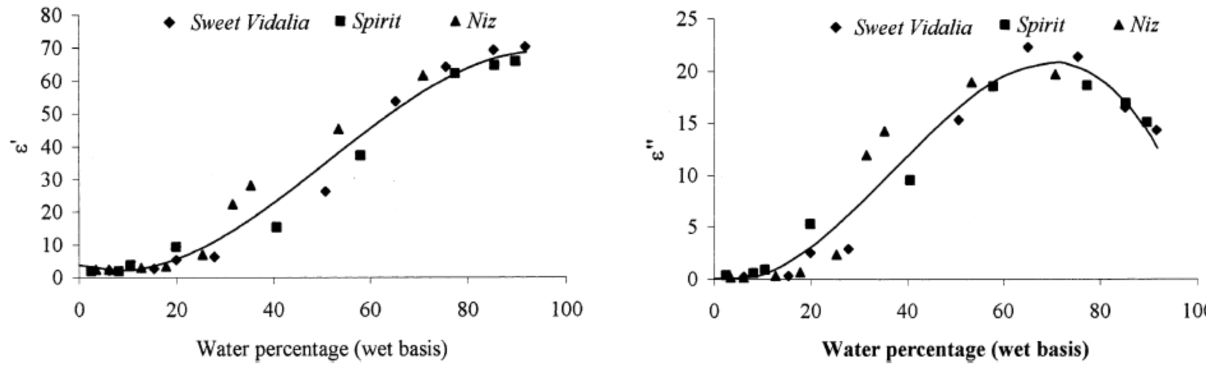
$$\varepsilon'' = \varepsilon_d''(\omega) + \varepsilon_c''(\omega) \tag{1.4}$$

The dielectric properties of agricultural products have been studied extensively because of their usefulness in determining bulk properties of granular materials. Among these bulk properties, the most important from an agricultural and economic standpoint are moisture and bulk density (Nelson 1980). Relationships between dielectric properties and moisture have been established that show the frequency, density, and temperature dependence of cereal grains in both the radio (Nelson 1973) and microwave (Trabelsi 2006) regions of the electromagnetic spectrum. Other influencing factors such as chemical composition and sorption-desorption cycles were shown to have smaller effects (Nelson 1981).

The volume of research in microwave sensing technologies in the higher moisture range (30% to 90%) is much less, relative to research in lower moisture materials (1% to 25%). These higher ranges of moisture contents include the typical moisture content of Vidalia Onions. On average, the interior of a Vidalia onion contains about 85% to 90% moisture on the wet-basis (Maw et al. 1996).

Some preliminary work has been done on measuring the dielectric properties of Sweet Onions. The dielectric properties of three cultivars of onions were first reported at 2.45, 11.6 and 22 GHz by Nelson (1992). Dielectric properties were determined by rectangular waveguide measurements on fresh whole onion pieces. Reported in conjunction with the dielectric properties were the soluble solids content and moisture contents of the onions, but no attempt was made to deliberately vary these quality parameters.

More recently, a study reported dielectric properties of onions with a commercial open-ended coaxial-line probe at 2.45 GHz (Abhayawick et al. 2002). Onion samples from 0% to 92% moisture content were measured. Dielectric constant, ε', was changed from 1.6 to 66 with increasing moisture while dielectric loss, ε'', increased from 0.2 to 15.5. Figure 2.2a shows the variation of ε' in three onion varieties with moisture, while Figure 2.2b shows variation of ε'' with moisture



(a) *(b)*

Figure 2.4 Variation of dielectric properties with moisture content of three onion varieties at 2.45 GHz. *(a)* Dielectric Constant *(b)* dielectric loss factor (Abhayawick et al. 2002).

The nonlinear behavior in Figure 2.2a is explained through consideration of the binding of the water with the material. Water in materials exists in various binding conditions, ranging from tightly bound water to free water. Most materials have a critical moisture content below which water primarily exists as bound water (Schiffmann 1995). When water is more tightly bound, its ability to interact with microwave fields is diminished as indicated. This change is indicated by an inflection point where there is a change in the slope of the curve of moisture content plotted to dielectric properties. In Figure 2.2a this most likely occurs at approximately 40% moisture content. The nonlinear behavior of the curve in 2.2b is more difficult to explain. Here we see the dielectric loss factor peak at approximately 70% moisture content then the value begins to decline.

Open-Ended Coaxial-Line Probes

An open-ended coaxial-line probe is a cutoff section of a transmission line. When the contacting probe is applied to a flat face of a product, the signal reflected from this interface can be related to the dielectric properties. The reflection is characterized by the complex reflection coefficient and is calculated as:

$$\Gamma = \frac{Z_0 - Z_r}{Z_0 + Z_r} \tag{1.5}$$

where Z_0 is the characteristic impedance of the transmission line and Z_r is the impedance of the sample. Both numbers are complex which results in the following equation:

$$\Gamma = \frac{|Z_0|e^{j\theta_0} - |Z_r|e^{j\theta_r}}{|Z_0|e^{j\theta_0} + |Z_r|e^{j\theta_r}} \tag{1.6}$$

where $|Z_0|$ and θ_0 are the magnitude and phase angle, respectively, of the transmission line and $|Z_r|$ and θ_r are the magnitude and phase angle, respectively, of the sample.

The phase angle of the transmission line can be reduced to zero since there are negligible losses in the transmission line. Thus, equation (1.6) reduces to

$$\Gamma = \frac{Z_0 - |Z_r|e^{j\theta_r}}{Z_0 + |Z_r|e^{j\theta_r}} \tag{1.7}$$

By using the reflection coefficient, the dielectric properties of the sample can be calculated with the following equations (Nyfors and Vainikainen 1989):

$$\varepsilon' = \frac{-2|\Gamma|\sin\theta}{\omega C Z_0(1 + 2|\Gamma|\cos\theta + |\Gamma|^2)} \tag{1.8}$$

$$\varepsilon'' = \frac{1 - |\Gamma|^2}{\omega C Z_0(1 + 2|\Gamma|\cos\theta + |\Gamma|^2)} \tag{1.9}$$

where ω is the angular frequency in Hz, $\omega = 2\pi f$, and C is the capacitance of the fringing field. An equivalent circuit for the measurement setup is shown in Figure 2.5:

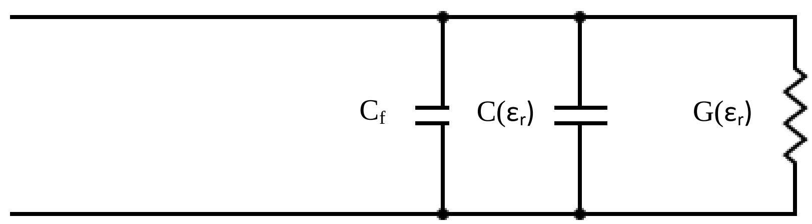


Figure 2.5 Equivalent circuit for the open-ended coaxial-line sensor

here, C_f, is capacitance of the fringing field inside the sensor, $C(\varepsilon_r)$ is the capacitance of the field outside the sensor, and $G(\varepsilon_r)$ is the radiation conductance.

The open-ended coaxial-line probe is useful for broad frequency range measurements that can extend from 200 MHz to 50 GHz. It is generally used in conjunction with a vector network analyzer for measurements on a wide range of materials (Baker-Jarvis et al. 1994). The advantages of this technique are easy sample preparation and its usefulness in measuring high-loss materials. It is especially useful for liquids. However, accuracy is poorer with low-loss samples and solids. When solids are measured, care must be taken to ensure proper contact with the probe (Agilent_Technologies 2008). Nonhomogeneity of the dielectric sample can also affect accuracy as the open-ended coaxial-line probe provides information on a small volume of the sample. Due to the nature of the derivation of the dielectric properties from the reflection coefficient calculated, dielectric properties can have different uncertainties. For values of the dielectric constant less than 20 there is a large change of the reflection coefficient for small changes of the dielectric constant. In this region, dielectric measurement is more sensitive and precise. On the contrary, for dielectric constants higher than 70 there is little change in the reflection coefficient, which results in a measurement with more uncertainty. Illustrated in Figure 2.5 is a plot of dielectric constant versus the reflection coefficient.

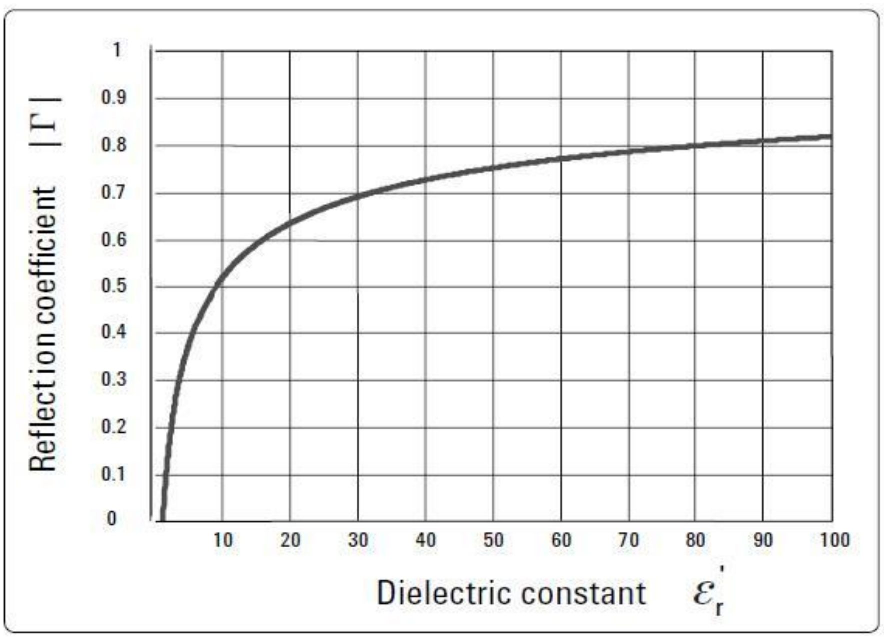


Figure 2.6 A plot of the calculated dielectric constant versus the reflection coefficient shows that for smaller dielectric properties, there is a large change in the reflection coefficient. Conversely,

for larger dielectric properties there is a small change in the reflection coefficient. (Agilent_Technologies 2006).

Open-ended coaxial-line probes are commercially available, and much research has been performed with them in varied fields ranging from medicine to measurement of liquids and soil moisture. Research performed with open-ended coaxial-line probes sensed dielectric properties of biological tissues *in vivo* (Stuchly et al. 1982). Measurement of the dielectric properties of solids to determine uncertainty showed that by using empirical relationships the uncertainty could be made comparable to measurement of liquids (Jiang et al. 1993). Use of the probe for quality sensing of honeydew melons was also attempted. The results of predicting soluble solids content were inconclusive (Nelson et al. 2006). Many other fresh fruits and vegetable have been studied as well (Nelson 2002). A study on alfalfa leaves showed that different density-independent equations could be used for moisture prediction (Shrestha and et al. 2005) . Work performed on investigating sensing volume of open-ended coaxial-line probes showed that an assumption of homogeneity should be made for a region extending in a hemispherical shape 1.25 to 3.75 mm from the probe surface (Hagl et al. 2003).

CHAPTER 3

DIELECTRIC SPECTROSCOPY MEASUREMENTS FOR MOISTURE PREDICTION IN VIDALIA ONIONS[1]

[1] McKeown, M.S., Trabelsi, S., and Tollner, E.W. Submitted to *Journal of Food Engineering*, 9/16/2011

Abstract

Microwave sensing offers an opportunity to determine nondestructively the amount of moisture in materials by sensing the dielectric properties of the material. Dielectric properties of Vidalia onions grown in southeastern Georgia were measured with an open-ended coaxial-line probe and network analyzer in the range from 200 MHz to 20 GHz. Frequency dependence and moisture dependence of dielectric properties were analyzed for moisture contents between 8% and 91%. Moisture content was linearly correlated with the dielectric constant at higher frequencies for the entire moisture range. A density-independent function that incorporates both the dielectric constant and loss factor was tested across multiple frequencies and moisture ranges. Use of this function enabled prediction of moisture content with high accuracy ($R^2 = 0.99$) up to 40% moisture content.

Introduction

Dielectric properties are the fundamental electric properties that characterize the interaction of nonconducting materials with an electric field. It is well known that moisture content of materials can be sensed nondestructively through the use of these properties (Nelson 1973). Dielectric properties are expressed in terms of the relative complex permittivity:

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{3.1}$$

here, the real part ε' is defined as the dielectric constant which is associated with the electric energy stored in the material relative to a vacuum, which is valued at 1. The imaginary part ε'' is the dielectric loss factor, which is associated with the energy lost in the material, and j is the imaginary unit $j = \sqrt{-1}$. In general, dielectric properties are dependent on frequency, temperature, moisture, and composition of the material (Hasted 1973).

Vidalia onions are a type of sweet onion (*Allium cepa* L.) grown in a region of southeast Georgia as defined by Georgia and Federal Law (USDA 1989). Specifically, Vidalia onions are of the Granex yellow onion variety. In 2009, based on a survey of Georgia county extension agents, the Vidalia onion crop was valued at $126,107,748 (UGA 2010). Prior to storage, Vidalia onions must be cured. Curing is an essential step that seals the moisture in the interior of the onion from the outside environment. This forms a barrier to the intrusion of disease during post-harvest storage and shipping (Maw et al. 1997). When properly done, curing involves cauterizing incisions that may exist in the outer ring, drying the outer skin, and sealing the neck and roots. Curing can be done either artificially or naturally. Currently, this process is controlled simply by time and human visual inspection (HVI) (Maw et al. 2004). However, varietal and year-to-year differences can require fine tuning of the curing procedure. If a method of sensing the curing of the onion skin could be developed, this would enable a more efficient curing process.

The dielectric properties of agricultural products have been studied extensively because of their usefulness in determining bulk properties of granular materials (Kent and Jason 1975; Kraszewski 1978; Trabelsi et al. 1997). Among these bulk properties, the most important from an agricultural standpoint are moisture and bulk density (Nelson 1981). Relationships between dielectric properties and moisture have been established that show the frequency, density, and temperature dependence of cereal grains in both the radio-frequency (Nelson 1973) and microwave (Trabelsi 2006) regions of the electromagnetic spectrum. Other influencing factors such as chemical composition and sorption-desorption cycles were shown to have smaller effects (Nelson 1981).

There is very little published research on the use of dielectric properties to predict quality attributes of onions. The dielectric properties of three cultivars of onions were first reported at 2.45, 11.6 and 22 GHz by Nelson (1992) as determined by rectangular waveguide measurements. Later, dielectric properties at a single frequency were measured for three varieties of onions, and variation with moisture content and temperature were shown (Abhayawick et al. 2002). Other nondestructive sensing techniques have been applied to onions, including a gas sensor to detect sour skin rot (Li et al. 2009). Hyperspectral imaging was used to detect sour skin in onions (Wang et al. 2011). An X-ray system has also been applied to classify onions by size and as either satisfactory or defective (Tollner et al. 2005).

In this study, measurements were made on Vidalia onions at different moisture contents in a band of frequencies from 200 MHz to 20 GHz. From these broad-range measurements, certain frequencies were investigated for their usefulness in predicting moisture content. In addition, a density-independent function expressed in terms of the dielectric properties was applied to the data to predict moisture content with a high level of accuracy up to 40% moisture content.

Materials and Methods

Vidalia onions harvested in southeastern Georgia were obtained from the University of Georgia, Tifton Coastal Experiment Station. They were stored in a cold room (4 °C ± 1 °C) for two months prior to measurements and removed from the cold room a week before measurement. Investigation of sensing volume for open-ended coaxial-line probes showed that, with an assumption of homogeneity, the volume sensed extended in a hemispherical shape from 1.25 to 3.75 mm for certain probes and tissues (Hagl et al. 2003). Due to the heterogeneous nature of whole onion samples, it was decided to mince the sample prior to drying to ensure a sample with uniform moisture content. Prior to mincing, the two outermost layers were removed as well as the top and bottom regions of each onion. Samples were minced in a Black and Decker HC306[2] food chopper for ten seconds in two intervals of five seconds each. Once minced, onions were conditioned to lower moisture content levels by drying 50 g samples in a convection oven at 40 °C for different time periods. After removal from the oven, samples were placed in Ziploc bags and allowed to equilibrate for three days in a refrigerator at 4 °C. Afterwards, half of the sample was used for dielectric analysis and half was used for moisture content determination.

Reference Moisture

Reference moisture values were obtained through the gravimetric oven drying technique. No established method was found in the literature. After testing several methods for moisture determination, a technique used in a previous publication was deemed acceptable (Abhayawick et al. 2002). For each reference moisture measurement, two replicates between 2 and 10 g each were prepared from the minced onion samples and placed in 60-mm aluminum dishes. Samples were dried in a vacuum oven set at 70 °C and 0.1 atm (10.1325 kPa) for 7 h. Upon removal from the oven, samples were placed in a desiccator over anhydrous $CaSO_4$ and allowed to cool to room temperature. Moisture content of the samples was calculated on a wet-weight basis as follows:

$$M_{\%} = \frac{m_w}{m_w + m_d} \times 100 \qquad (3.2)$$

where $M_{\%}$ is the moisture content, m_w is the mass of the water in the sample, and m_d is the mass of the dry matter in the sample.

[2] Mention of company or trade names is for purpose of description only and does not imply endorsement by the U.S. Department of Agriculture or The University of Georgia

Dielectric Properties Measurements

An Agilent 85070E open-ended coaxial-line probe connected to a 5230C PNA-L Network Analyzer was used for dielectric properties measurements. When the probe is applied against the surface of a product, the measurements of the reflection coefficient are used to compute the dielectric properties. The 85070E probe was calibrated with air, a short, and glass-distilled water at 25 °C. Though primarily designed for liquids and solids with smooth surfaces, the probe can be used for semi solid measurements in certain circumstances (Agilent_Technologies 2008). Care was taken to ensure proper contact between the tip of the probe and the minced onion sample. Penetration depth was calculated to ensure an 'infinite' medium (Metaxas and Meredith 1983):

$$\delta_p = \frac{c}{2\pi f\sqrt{2\varepsilon'}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)^{1/2}} \tag{3.3}$$

where δ_p is the penetration depth, c is the speed of light in a vacuum, f is the frequency in Hertz, ε' is the dielectric constant, and ε'' is the dielectric loss factor.

Minced onions were loaded into a stainless steel sample holder with a minimum thickness of 3mm. This thickness was used to ensure an 'infinite' medium for the material. Dielectric properties were calculated from the reflection coefficient by the 85070E dielectric probe kit software. The measurement frequency range was 200 MHz to 20 GHz with 101 logarithmically distributed points. Triplicate measurements of each sample were taken and averaged. A force monitoring load cell (Nelson 2010) was used to ensure constant pressure applied to each sample, 215 – 250 kPa. All measurements were performed at room temperature (23 °C). Measurement system is shown in Figure 3.1.

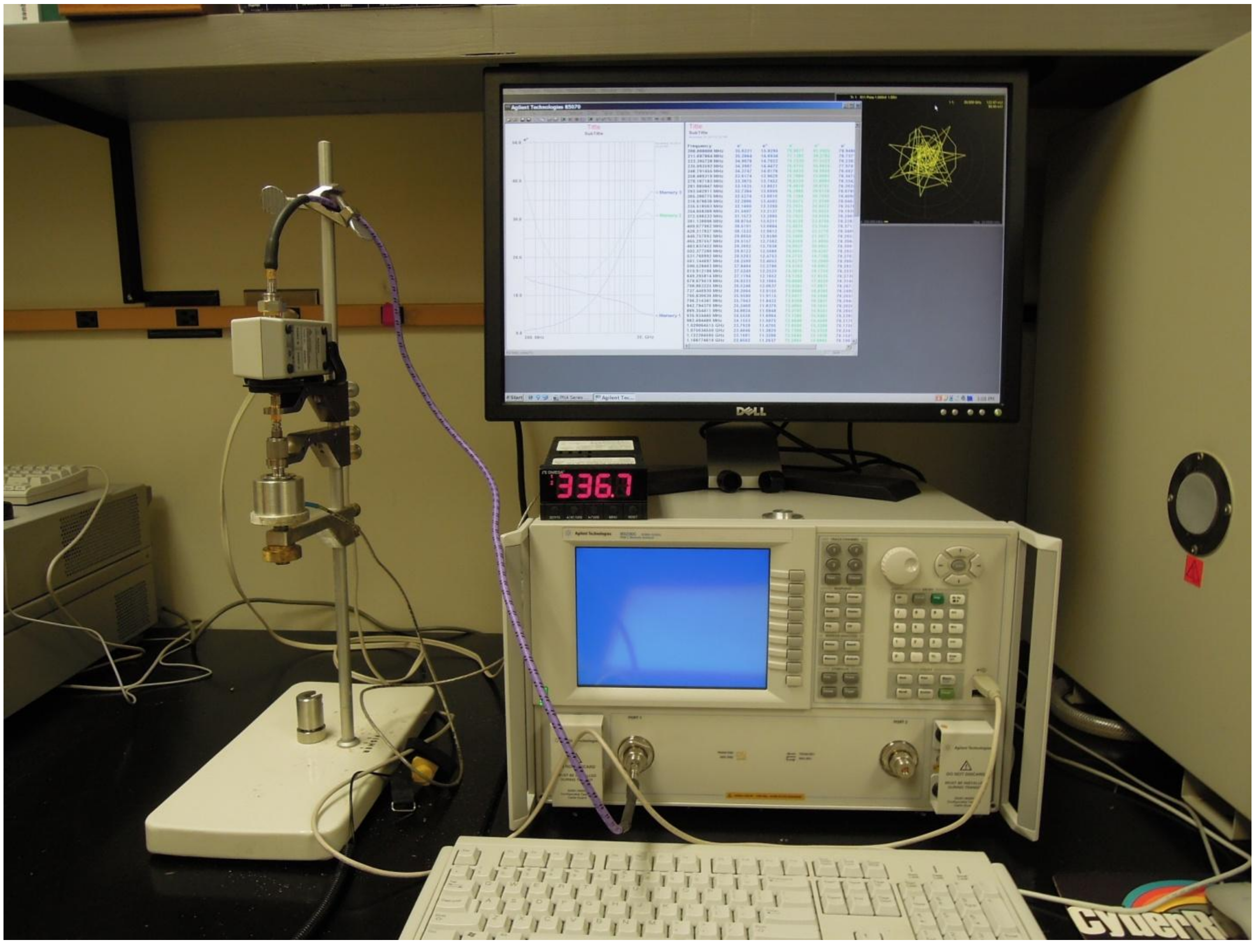


Figure 3.1 Measurement setup showing network analyzer connected to open-ended coaxial-line probe with sample loaded onto force gauge system

Results and Discussion

Frequency Dependence of Permittivity

Spectral data for ε' and ε'' are shown in Figures 3.2 and 3.3 for the frequency range from 200 MHz to 20 GHz. In Figure 1 the trend for ε' with increasing moisture is increasing at all frequencies. The ε'' values have more complex behavior with changes in measurement frequency. The loss factors are influenced by many different mechanisms dependent on the material and the frequency of measurement. Generally, there are five different loss mechanisms that can contribute to the ε' value. For the frequency range used in this study, electronic, atomic and interfacial polarizations have no significant effects which results in the dependence of ε'' being solely a function of dipolar polarizations and ionic conductivity (Kraszewski 1996):

$$\varepsilon'' = \varepsilon_d''(\omega) + \varepsilon_c''(\omega) \tag{3.4}$$

where $\omega = 2\pi f$ is the angular frequency, the subscript d denotes the dipolar polarization, and the subscript c denotes the ionic conductivity defined as:

$$\varepsilon_c''(\omega) = \frac{\sigma}{2\pi f \epsilon_0} \tag{3.5}$$

where σ is the conductivity (S/m), f is the frequency, and the permittivity of free space $\epsilon_0 = 8.854 \times 10^{-12}$ (F/m).

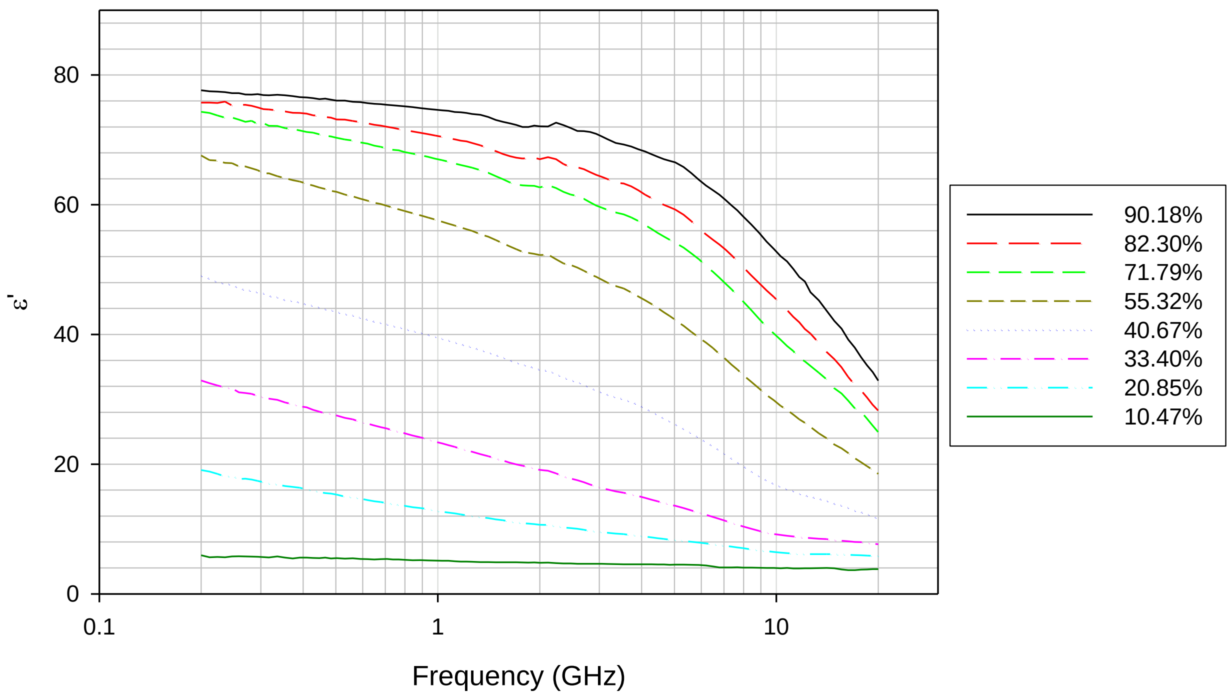


Figure 3.2 Measured dielectric constant of minced onion as a function of frequency for indicated moisture contents

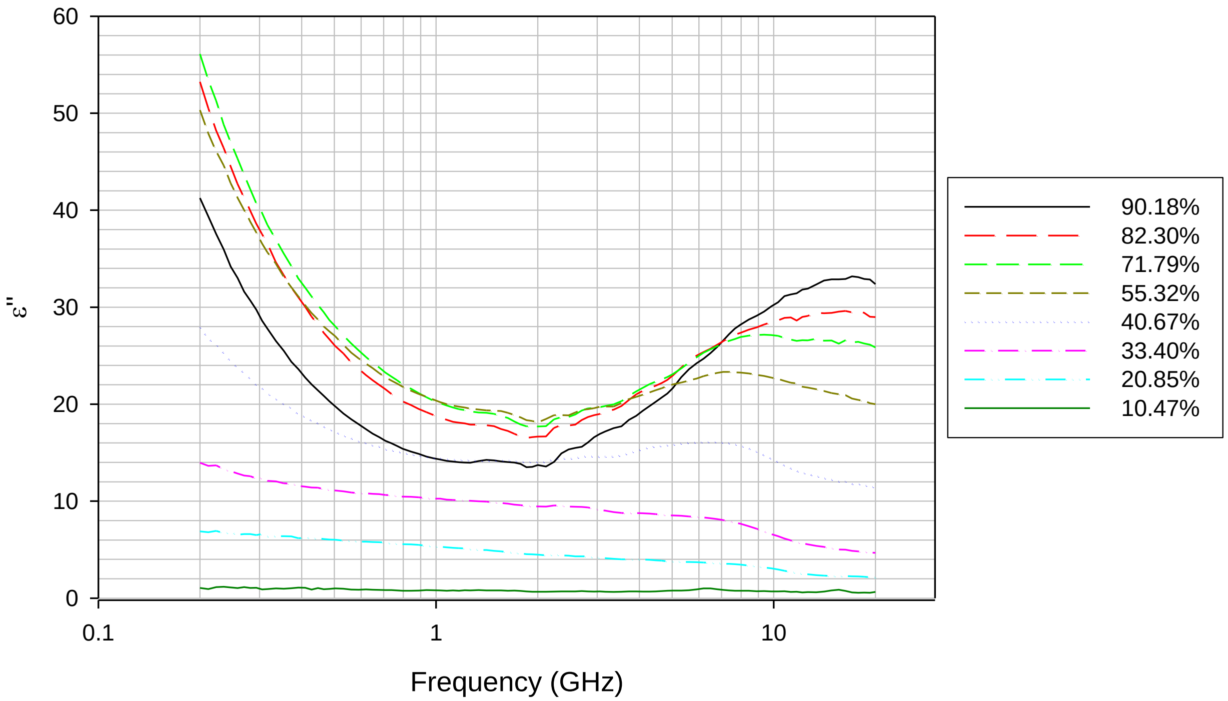


Figure 3.3 Measured dielectric loss factor of minced onion as a function of frequency for indicated moisture contents.

As shown in Figure 3.3 there is a distinct shift in the effect of moisture content on the spectral curve. Initially, in the range from 200 MHz to approximately 1-2 GHz, the ionic conductivity mechanism dominates the loss factor. Here, the loss factor follows a pattern of increasing with increasing moisture content up to about 60-70% moisture content. Beyond this point, the loss factor begins to decrease with moisture content. This behavior might be explained in two parts. Initially, with added moisture, the cations and anions in the material are increasingly able to displace with the changing electric field. After a certain point, the ions sensed at the contacting face of the probe may become less concentrated and hence contribute less to the overall dielectric loss factor. In the region of 1 - 2 GHz there is a shift in the predominant dielectric relaxation mechanism and from above 2 GHz the dipolar alignment mechanism dominates. In this region, the permanent dipole of the water molecule realigning with the electric field causes an increase in the dielectric loss factor up to a peak after which it trends downward. At this point the molecule can no longer realign as fast as the electric field is alternating. This is known as the relaxation frequency and it is shown to increase with frequency as the moisture content in the material is increased.

Moisture Dependence of Permittivity

Both the dielectric constant and dielectric loss factor are highly dependent on moisture content (Nelson and Stetson 1976; Trabelsi et al. 1995). The behavior with changing moisture is highly dependent on frequency. Figures 3.4 and 3.5 show the dielectric constant and loss factor respectively for 502.4 MHz. Here, the dielectric loss factor to begin to decrease at approximately 60% moisture content. Figures 3.6 and 3.7 show both dielectric properties at a frequency of 2.468 GHz, which near the ISM frequency of 2.45 GHz. Here again, the dielectric constant increases in a nearly linear fashion, and the dielectric loss factor increases up to approximately

60% moisture content and then decreases. At higher frequencies both ε' and ε'' increase in nearly a linear fashion with moisture content. Figures 3.8 and 3.9 show the dielectric constant and loss factor for 13.36 GHz. Here, the plot can be divided into two linear regions with different slopes. The two different slopes are indicative of various stages of binding of water to the material (Kraszewski 1996). The smaller slope in the lower range of moisture content is due primarily to bound water, while the larger slope in the high range is due to the increasing presence of less tightly bound water. The region where the change of slope occurs is a characteristic of the material and is known as the critical moisture, M_c (Stuchly 1970).

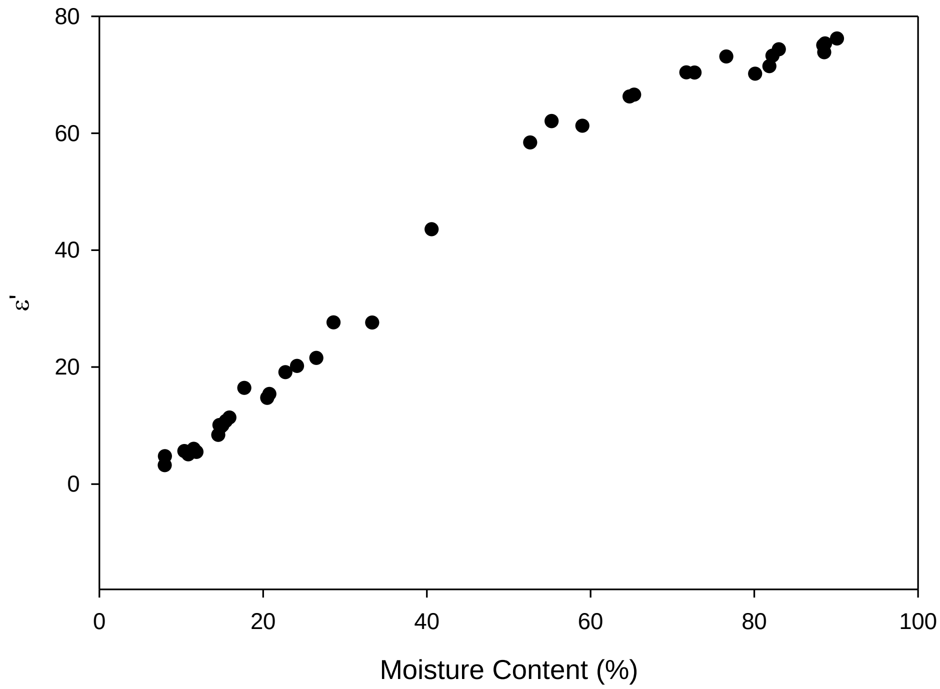


Figure 3.4 Moisture dependence of the dielectric constant of minced onion at 502.4 MHz

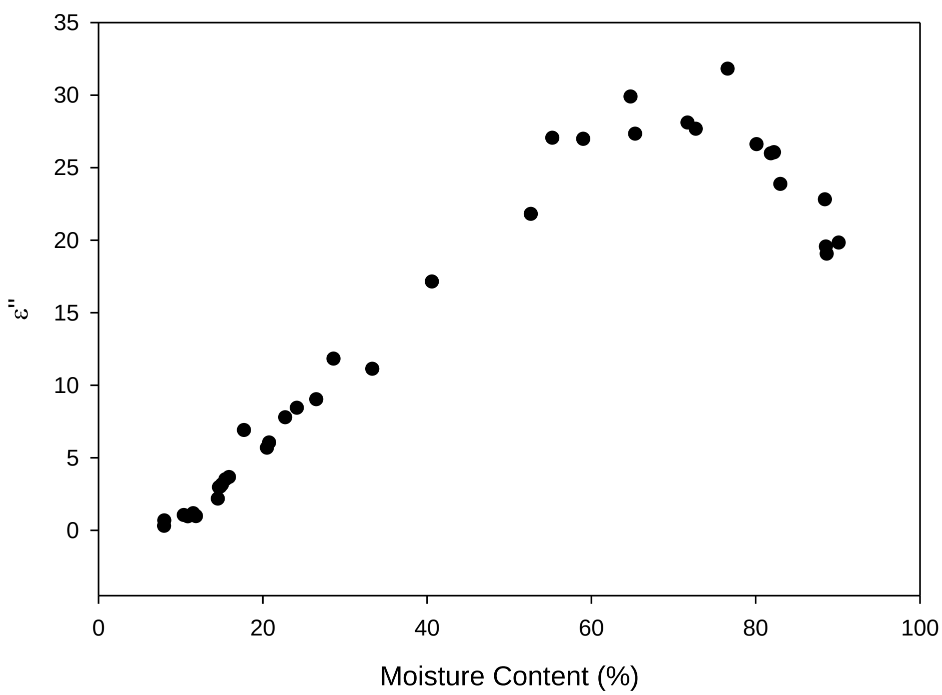


Figure 3.5 Moisture dependence of the dielectric loss factor of minced onion at 502.4 MHz.

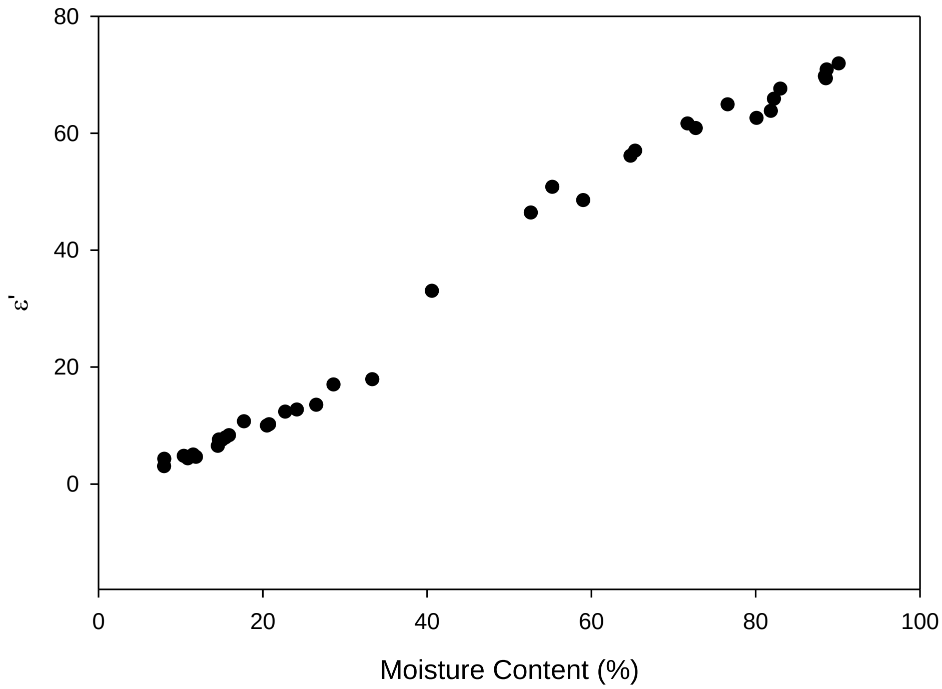


Figure 3.6 Moisture dependence of the dielectric constant of minced onion at 2.468 GHz.

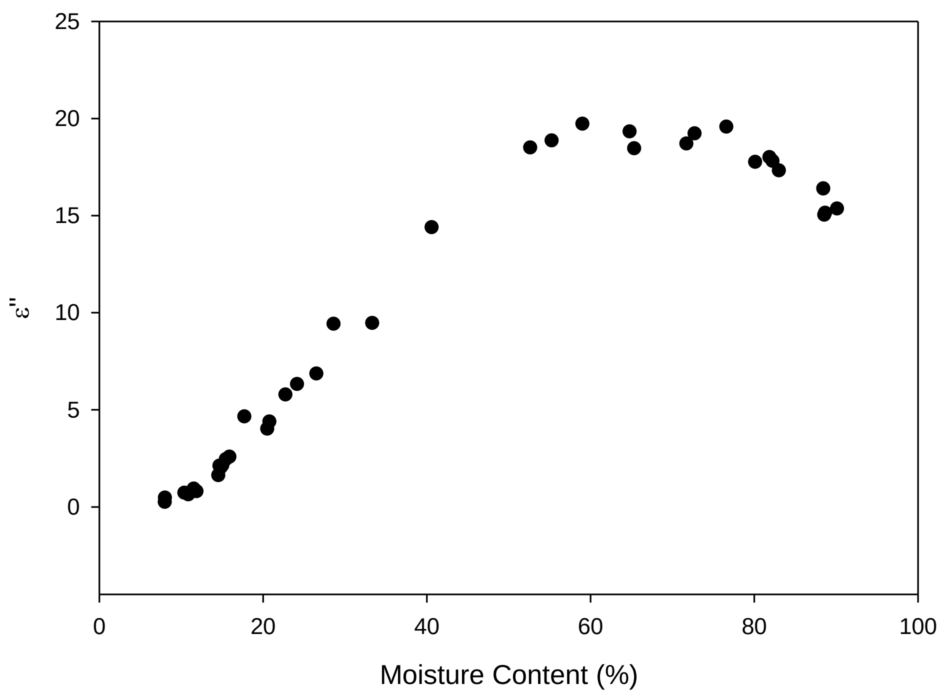


Figure 3.7 Moisture dependence of the dielectric loss factor of minced onion at 2.468 GHz.

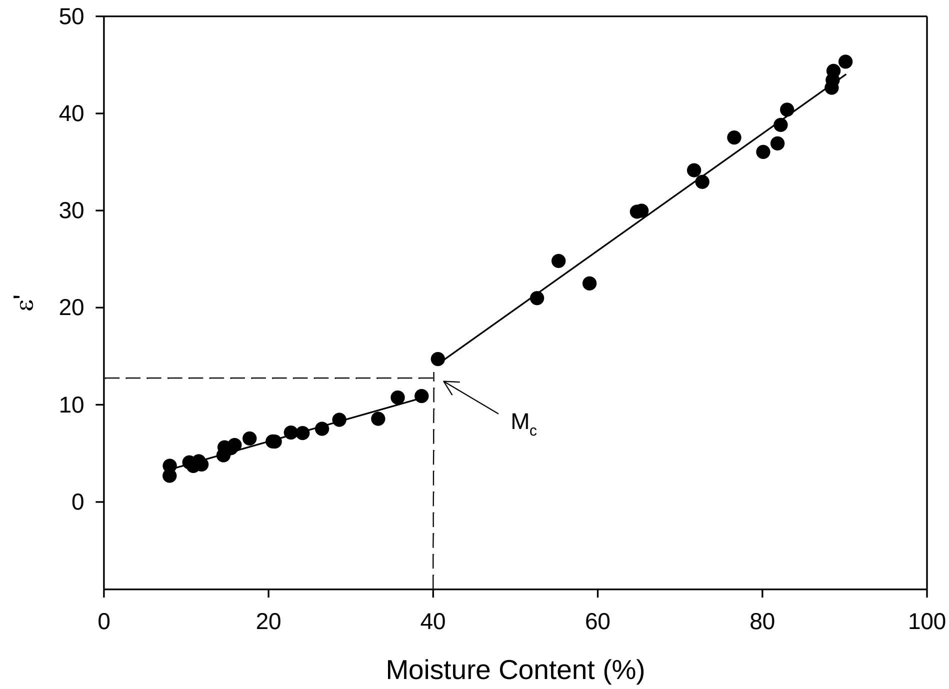


Figure 3.8 Moisture dependence of the dielectric constant of minced onion at 13.36 GHz

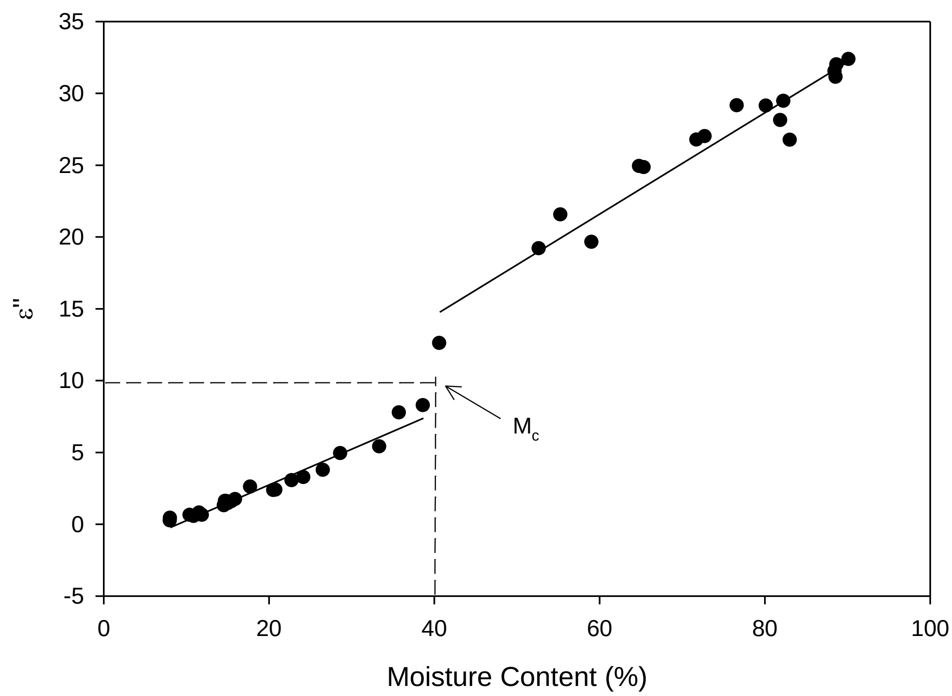


Figure 3.9 Moisture dependence of the dielectric loss factor of minced onion at 13.36 GHz

Density-Independent Moisture Functions

It is well established that variations in bulk density have been known to affect moisture prediction accuracy. Therefore calibration functions for moisture prediction independent of density were developed for bulk granular materials. (Jacobsen et al. 1980; Kent and Kress-Rogers 1986; Kraszewski et al. 1998; Trabelsi et al. 1998). However, attempts have been made to use these with other materials with some success (Shrestha and et al. 2005). Thus it was decided to attempt to use a density-independent function that incorporates both ε' and $\varepsilon''$to predict moisture content with more accuracy. The function chosen is listed below (Meyer and Schilz 1980):

$$A_\varepsilon = \frac{\varepsilon''}{(\varepsilon' - 1)} \tag{3.6}$$

This function uses the relationship between the dielectric loss factor and the dielectric constant. Since both the dielectric constant and loss factor are density dependent, a ratio of both values eliminates the effect of density. Although density was not specifically measured in this study, it was thought that the function would compensate for the slight variations in the applied pressure, which affects the density of the sample. As shown in Figures 3.10 – 3.13 plotting this function at 2.46 GHz, 7.08 GHz, 10.29 GHz, and 13.35 GHz provides for linear behavior of the with moisture content up to 40%. Beyond this point, the function does not vary linearly with moisture content. This may indicate the function only operates in the region of bound water. This reinforces the previous evidence that showed the critical moisture content is at approximately 40%. Use of this function allows models to be developed with very high coefficients of determinations up to 40% moisture content.

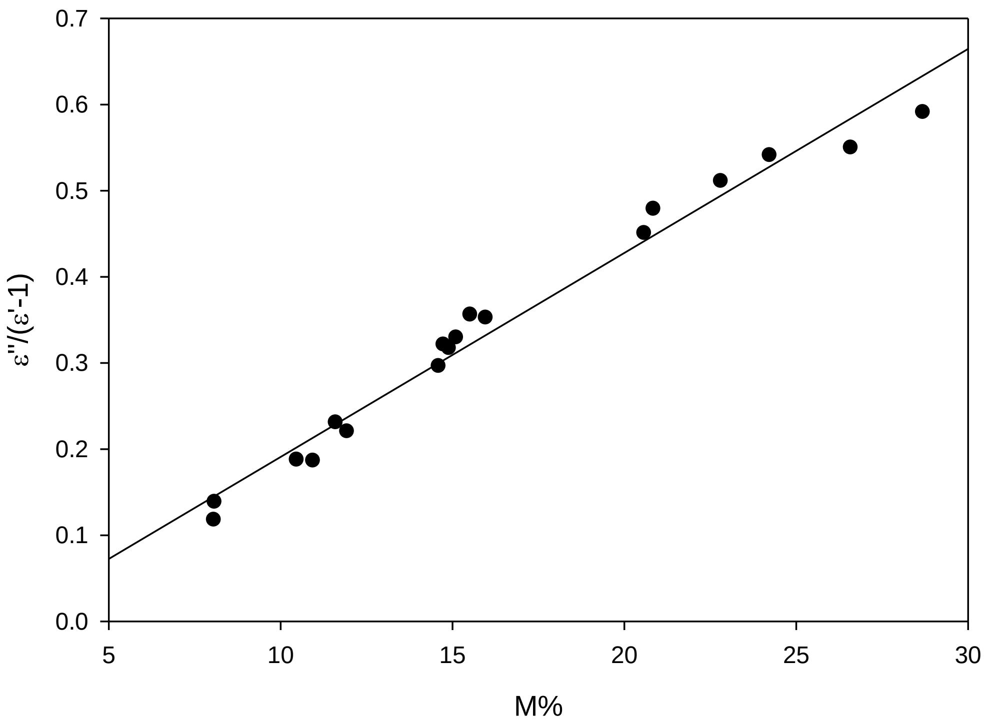


Figure 3.10 Density-independent function, ε"/ (ε'-1), used at 2.468 GHz for minced onions

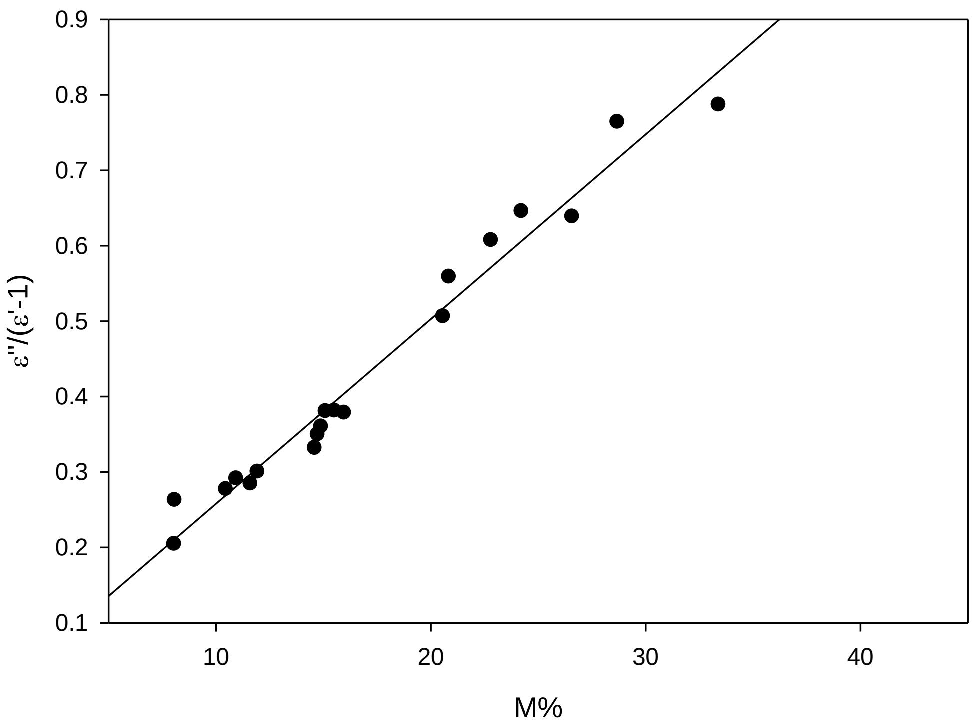


Figure 3.11 Density-independent function, ε"/ (ε'-1), used at 7.08 GHz for minced onions

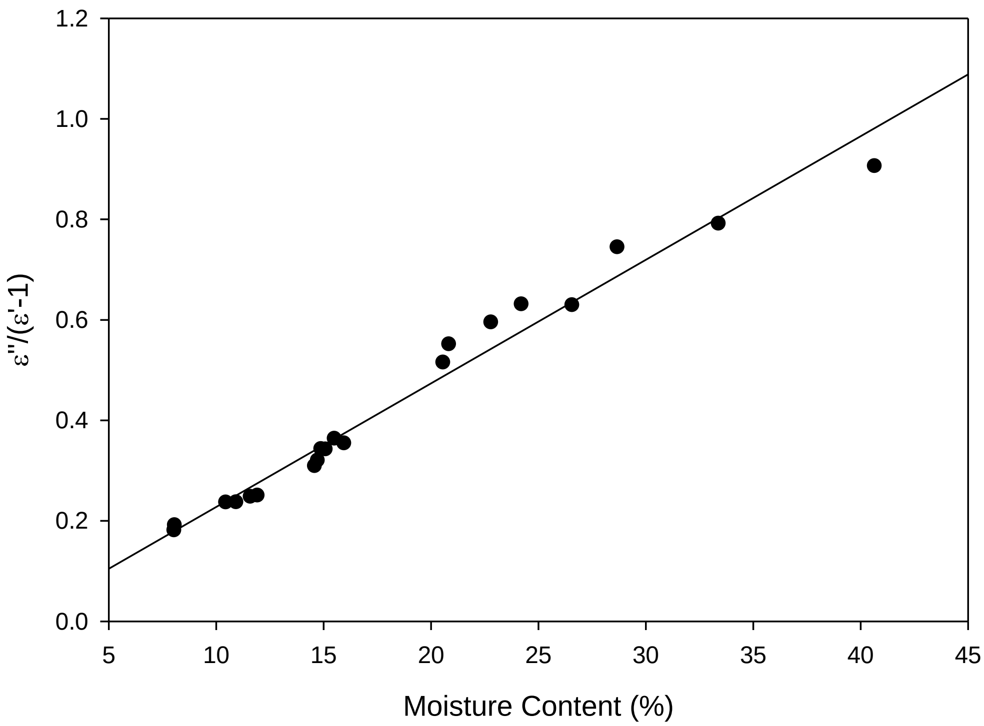


Figure 3.12 Density-independent function, ε"/ (ε'-1), used at 10.29 GHz for minced onions

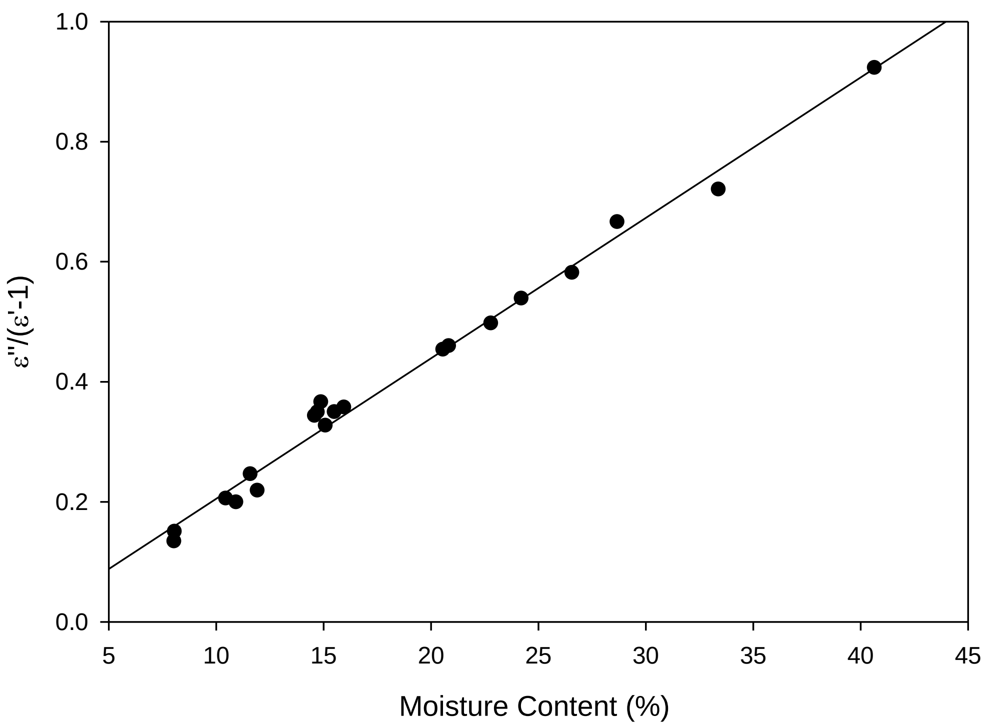


Figure 3.13 Density-independent function, ε"/ (ε'-1), used at 13.36 GHz for minced onions.

In Table 3.1, the linear model for predicting moisture content is shown for seven different frequencies. Presented are the frequency, the moisture range used, the slope, the intercept, the coefficient of determination (R^2), the standard error of calibration, and the standard error of performance.

The equation for moisture prediction is given the following form:

$$A_\varepsilon = b_1 M_{\%} + b_0 \tag{3.7}$$

$$M_{\%} = \frac{A_\varepsilon - b_0}{b_1} \tag{3.8}$$

where A_ε is the density-independent function, $M_{\%}$ is the moisture content, b_1 is the slope, and b_0 is the intercept.

In order to evaluate the calibration effectiveness of the model as listed in Table 3.1, the standard error of calibration was calculated:

$$SEC = \sqrt{\frac{1}{n-p-1}\sum_{i=1}^{n}(\Delta e_i)^2} \tag{3.9}$$

where n is the number of observations, p is the number of independent variables, and Δe_i is the difference between the predicted value of moisture and that determined by a standard method for the *i*th sample.

In order to validate the model, a standard error of performance was calculated from a set of observations that were not used in the calibration as follows:

$$SEP = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\Delta e_i - \overline{\Delta e})^2} \tag{3.10}$$

where $\overline{\Delta e}$ is:

$$\overline{\Delta e} = \frac{1}{n}\sum_{i=1}^{n}\Delta e_i \tag{3.11}$$

The moisture ranges included in Table 3.1 correspond to the regions where the A_ε function had linear behavior. Beyond this maximum moisture range, the resulting A_ε would begin to decrease with increasing moisture content. As the frequency used in the model was increased, a greater range of moistures could be included in the linear model. Also included for each frequency in the table is a lower moisture range that extended to 20.85% which would include the endpoint region in a drying or curing process.

Table 3.1 Model for prediction of moisture content at selected frequencies and moisture ranges. Also given are the slope, intercept, coefficient of determination (R^2), standard error of calibration (SEC), and standard error of prediction (SEP).

Frequency (GHz)	*Moisture Range (%)*	*Slope, b_1*	*Intercept, b_0*	*R^2*	*SEC*	*SEP*
0.502	8.06 - 20.85	0.02123	-0.0009	0.9283	1.1369	1.3510
1.024	8.06 - 20.85	0.02678	-0.0852	0.9653	0.7865	0.8078
2.468	8.06 - 20.85	0.02755	-0.0960	0.9857	0.4929	0.5302
	8.06 - 24.23	0.02633	-0.0810	0.9888	0.5450	0.5231
5.905	8.06 - 20.85	0.02693	-0.0358	0.9793	0.5955	0.8292
	8.06 - 28.29	0.02572	-0.0199	0.9883	0.6959	0.8996
7.081	8.06 - 20.85	0.02321	0.0270	0.9380	1.0518	1.0622
	8.06 - 33.04	0.02448	0.0132	0.9730	1.2296	1.1323
10.29	8.06 - 20.85	0.02729	-0.0602	0.9628	0.8038	0.6316
	8.06 - 40.67	0.02460	-0.0184	0.9751	1.4293	1.0154
13.36	8.06 - 20.85	0.02600	-0.0687	0.9660	0.8330	0.8217
	8.06 - 40.67	0.02340	-0.0288	0.9887	0.9574	1.1095

Conclusions

Dielectric properties were measured for minced Vidalia onion samples between 200 MHz and 20 GHz. These data were analyzed with respect to frequency and moisture dependence. Frequency analysis showed a nearly linear increase in the dielectric constant with rising moisture content at all frequencies. The dielectric loss factor exhibited similar behavior in the higher frequency range. Dielectric properties were plotted against moisture contents in the range from 8.1% to 90.2% showing that models could be developed for predicting moisture content from dielectric properties. By using a previously reported density-independent function of the dielectric properties, models were developed that predicted moisture content with a high degree of accuracy up to the critical moisture content of 40%. The frequency dependence of these properties of Vidalia onions could potentially help in selecting an optimal frequency for moisture prediction. Based on the results of this study, use of a density-independent function of the dielectric properties provided the best prediction of moisture content at higher frequencies. These data could be used to develop a sensor that could be used in quality control of Vidalia onions in the future.

Ideally, a future sensor would utilize a single frequency to measure and predict moisture content. Based on the results of this study, that frequency should be selected in the higher measured frequency range. In this study, using 13.36 GHz achieved the greatest accuracy and range of prediction. It is expected that the accuracy of the prediction would increase even further as the frequency used is increased, up to 19-21 GHz which is the relaxation frequency of pure water. However, consideration must be taken to balance cost, which typically increases with frequency, and penetration depth, which decreases with increasing frequency.

Acknowledgements

The author would like to thank Changying Li, Assistant Professor, University of Georgia, Tifton, GA for providing the onion samples used in the study. This project was partially funded by the United States Department of Agriculture, National Institute of Food and Agriculture Specialty Crop Research Initiative (Award No. 2008-51180-19579).

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CHAPTER 4

DIELECTRIC SPECTROSCOPY FOR TEMPERATURE-CORRECTED MOISTURE PREDICTION IN VIDALIA ONIONS[3]

[3] Mckeown, M.S., Trabelsi, S., and Tollner, E.W. To be submitted to *Transactions of the American Society of Agricultural and Biological Engineers.*

Abstract

The use of microwave sensing offers an opportunity to determine nondestructively the amount of moisture in materials by sensing the dielectric properties of the material of interest. However, it is well documented that changes in temperature can significantly affect these measurements. In this study, dielectric properties of Vidalia onions were measured with an open-ended coaxial-line probe and network analyzer at different moisture contents and different temperatures in the range from 200 MHz to 15 GHz. Frequency, moisture, and temperature dependence of the dielectric properties were studied for moisture contents between 6% and 92%. Results showed that dielectric properties can be directly or inversely related to temperature, depending on the moisture content of the onion tissue and the frequency used. By using a previously reported density-independent function, models for moisture prediction were generated that include compensation for changes in temperature.

Introduction

Dielectric properties are the intrinsic electrical properties that describe how poorly conducting materials interact with an electric field. They consist of two parts expressed as a relative complex permittivity:

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{4.1}$$

Here, the real part, ε' is the dielectric constant, and is associated with the electric energy stored in the material relative to a vacuum, which is valued at 1. The imaginary part, ε'' is the dielectric loss factor, which is associated with the energy lost in the material, and j is the imaginary unit $j = \sqrt{-1}$.

Dielectric properties of lossy materials are a function of frequency and are affected by the moisture, temperature, density, and chemical composition of the material in question (Nelson 1981). Though moisture content dominates the effect on dielectric properties, temperature has been documented to cause significant changes in the values as well. In fact, measurements on corn and wheat showed the effects of moisture and temperature can be interchangeable (Trabelsi et al. 1997).

Vidalia onions (*Allium cepa* L.) are a type of the Granex Yellow onion variety known for its sweetness. In 2009, the Vidalia onion crop yield was valued at $126,107,748 (UGA 2010). Vidalia onions are grown in southeast Georgia as defined by Georgia and Federal Law (USDA 1989). Prior to storage, these onions must have their outer layers dried either naturally or artificially in a process known as curing. This forms a barrier to introduction of disease into the fleshy interior of the onion.

The dielectric properties of agricultural products have been studied extensively for use in determining quality attributes (Kent and Jason 1975; Nelson 2006) . However, there is very little published research on the dielectric properties of onions. First published were dielectric properties of three cultivars of onions at 2.45, 11.6. and 22 GHz (Nelson 1992). Dielectric properties variations with moisture and temperature at 2.45 GHz have been measured (Abhayawick et al. 2002). Other nondestructive techniques have been explored but no work has been specifically aimed at determination of moisture content. Near infrared analysis was used for detection of dry matter content of onions (Birth et al. 1985). Hyperspectral imaging was also utilized to determine sour skin rot (Wang 2011). A gas sensor was utilized to determine sour skin rot (Li et al. 2009). Additionally, an X-ray sensor has been employed to detect internal sprouting and ring separations due to microbial rot in onions (Tollner et al. 1995). X-rays have also been used to detect and sort diseased onions (Tollner et al. 2005).

In this study, dielectric properties of minced Vidalia onions at different moisture contents were measured, examining changes with temperature and frequency. Temperature-dependent dielectric properties measurements were made in an environmental chamber in the range from 0 °C to 45 °C with 5 °C increments. Moisture contents measured ranged from 6% to 92%. Frequencies for the measurements ranged from 200 MHz to 15 GHz.

Materials and Methods

Sample Preparation

Onion samples were received from the University of Georgia, Tifton Coastal Experiment Station. Samples were stored in a cold room (4 °C ±1 °C) for two months preceding measurement. Material from the neck region, root region, and the two outermost layers of the onions were peeled away and removed. To achieve target moistures, onions were first minced in a Black and Decker HC306[4] food processor for homogeneity. Afterwards, 50 g samples were placed in disposable aluminum drying pans with perforated bottoms. Samples were then conditioned for different time periods in a forced air oven at 40 °C to achieve target moistures. Following removal from the oven, samples were placed in Ziploc bags and allowed to equilibrate for three days in a refrigerator at 4 °C

Reference Moisture

Reference moisture contents were obtained by a weight loss on drying technique (ADOGA 1976). Two replicates between 2–15 g were placed in 60 mm aluminum drying dishes. The samples were then loaded into a vacuum oven set at a temperature of 70 °C for 7 hours and 0.1

[4] Mention of company or trade names is for purpose of description only and does not imply endorsement by the U.S. Department of Agriculture or The University of Georgia

atm (10.1325 kPa). Samples were placed in desiccators over anhydrous $CaSO_4$ upon removal from the oven and allowed to cool to room temperature before weight measurement. Moisture content was determined on a wet-weight basis with equation (4.2).

$$M_{\%} = \frac{m_w}{m_w + m_d} \text{ x } 100 \qquad (4.2)$$

Here, $M_{\%}$ is the moisture content in percentage, m_w is the mass of water, and m_d is the mass of dry matter. All masses were measured to ± 0.0001g accuracy.

Dielectric Properties Measurement

For temperature-dependent measurements of the dielectric properties, both minced onion sample and the probe were fully enclosed in a temperature-controlled environment. Dielectric properties measurements were made with an Agilent 85070E open-ended coaxial-line probe connected to a 5230C PNA-L Network Analyzer. The network analyzer was calibrated with an open circuit, a short circuit, and glass distilled water at 25 °C. The dielectric properties were computed from the reflection coefficient. Frequencies measured were swept between 200 MHz and 15 GHz with 101 logarithmically distributed points. Temperature was controlled by using a Cincinnati Subzero MicroClimate MCB-1.2 Environmental Chamber. Temperature measurements were recorded with a thermocouple inserted into the wall of the stainless steel cup holding the sample used previously (Nelson et al. 1997). Dielectric properties were measured at temperatures between 0 and 45 °C in five-degree increments with 15 minutes allowed for temperature equilibration between measured points. A minimum sample thickness of 3 mm was used to ensure an “infinite” sample medium. Care was taken to ensure proper contact between the probe and sample. A photograph of the measurement setup is shown in Figure 4.1.

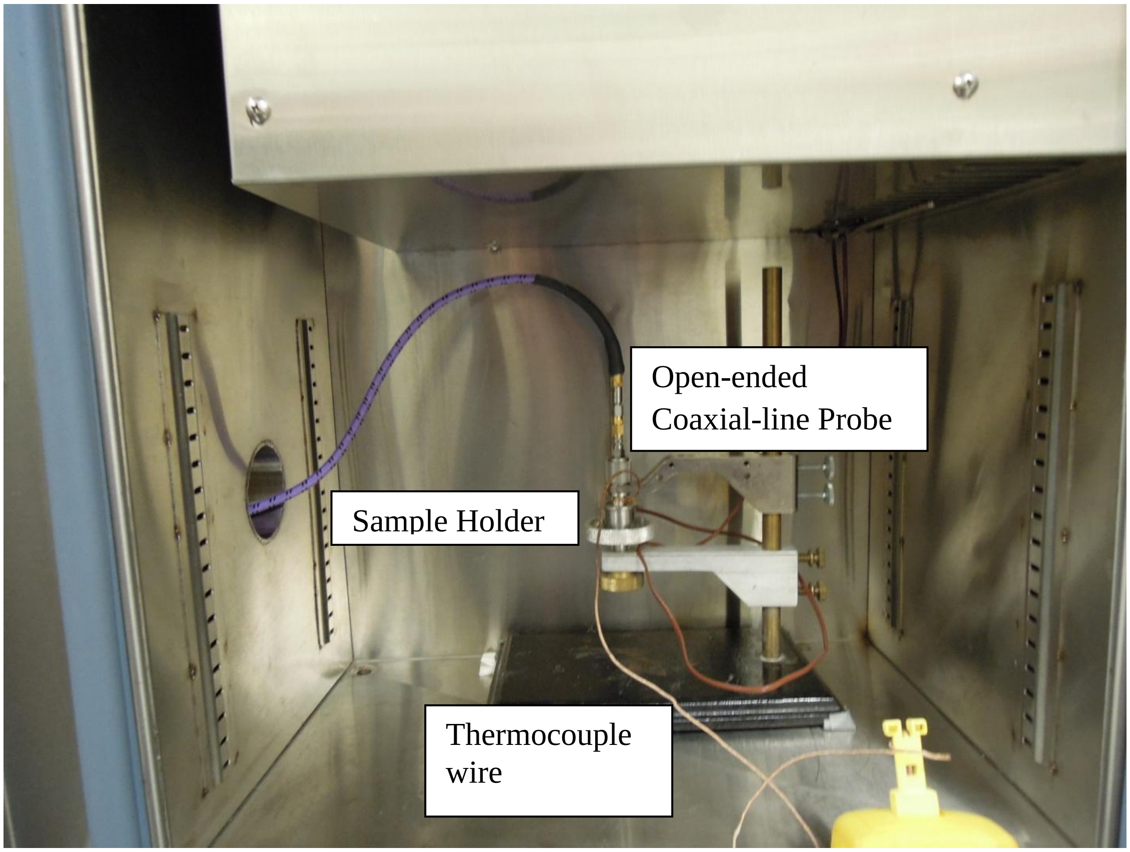

Figure 4.1 Photograph of the setup of the experiment showing the sample holder and probe both in the temperature controlled environment. Temperatures were recorded with a thermocouple inserted into a vertical hole drilled in the side wall of the stainless steelsample cup.

Results and Discussion

Frequency Dependence of Temperature

In order to grasp the overall trends that dielectric properties exhibit with changes in temperature, those change were plotted for three moisture contents. These moisture contents of 92.37%, 42.32 %, and 12.23% represent the moisture contents onion tissue can experience in three states, natural, at critical moisture, and dried. For the high moisture samples, the dielectric constant decreases with temperature at lower measured frequencies up to approximately 5 GHz. Beyond this frequency, a shift occurs and the trend is reversed, the dielectric constant increases with temperature as illustrated in Figure 4.2. The dielectric loss factor at high moisture contents increases with temperature at lower measured frequencies up to approximately 900 MHz. Beyond this point, the dielectric loss factor generally decreases with temperature; however, this trend is clouded by the shifting maxima of the curve of the dielectric loss factor. The peak value observed, which indicates the dielectric relaxation frequency is gradually shifting to higher frequencies with increased temperature as shown in Figure 4.3.

In the critical moisture region, the dielectric constant increases with temperature at all frequencies as shown in Figure 4.4. The dielectric loss factor in this moisture range increases with temperature in the lower and higher frequency regions of the measured frequencies as seen in Figure 4.5. Between frequencies of 1 and 3 GHz, there are two changes in the trend of the dielectric loss factor with temperature. However, in this region the change with temperature is so small, that it appears almost temperature independent.

For the low moisture region, 12.23 % the dielectric constant increases with temperature at all frequencies, though the effect of temperature is slightly greater at lower measured frequencies as shown in Figure 4.6. The dielectric loss factor at this moisture content approaches zero at 0 °C and increases at all frequencies with temperature as illustrated in Figure 4.7.

The dielectric properties change in proportion to their values with increasing temperature For example, at the 92.37% moisture level, a 5 °C increase in temperature can change the dielectric constant by approximately 4 to 5, while for the 12.32% moisture sample, a 45 °C increase in temperature increases the dielectric constant no more than 3.

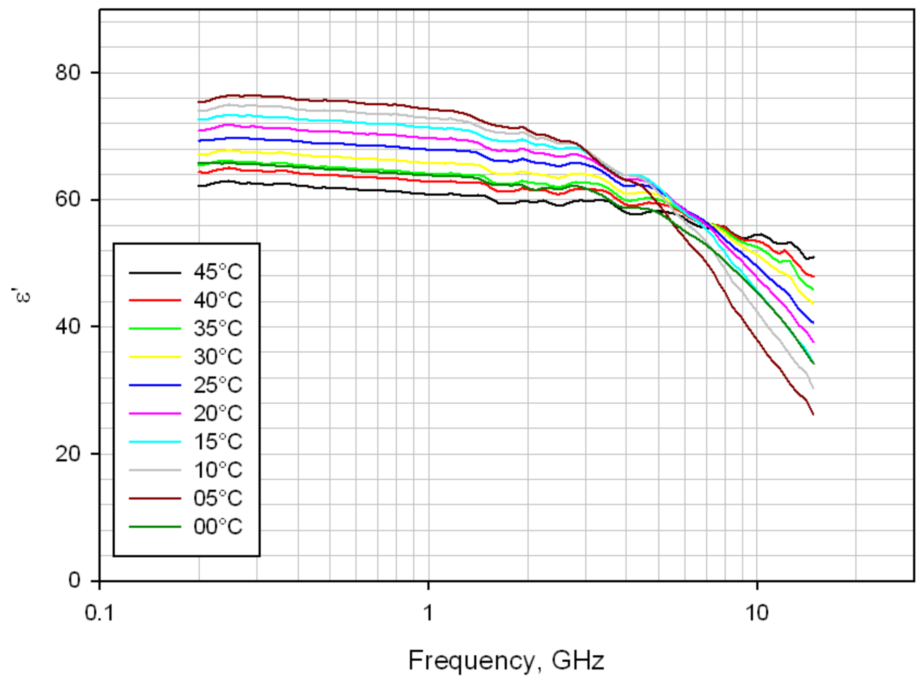

Figure 4.2 Measured dielectric constant as a function of frequency for indicated temperatures at 92.37% moisture content

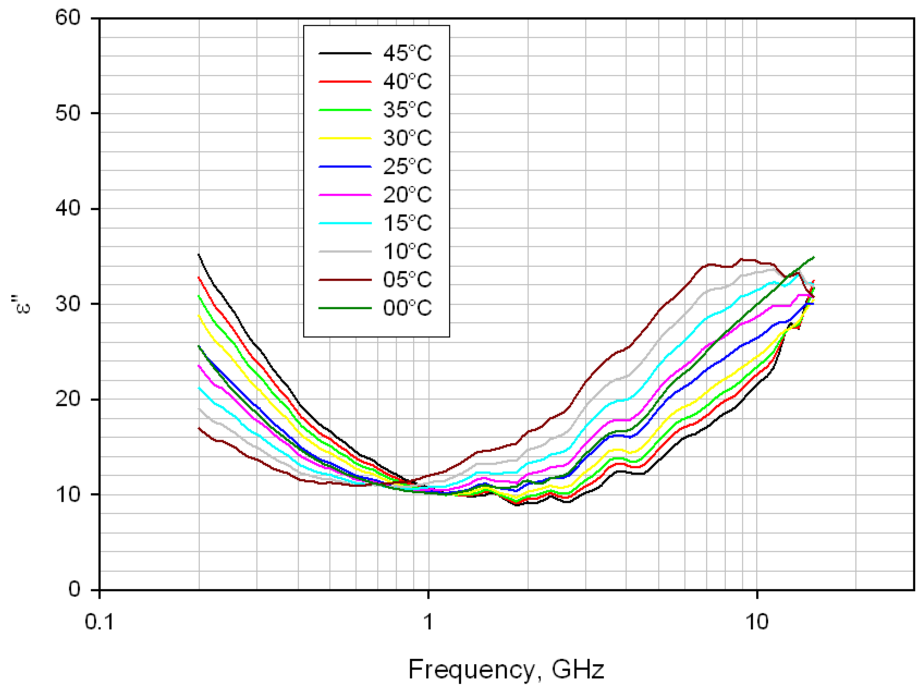

Figure 4.3 Measured dielectric loss factor as a function of frequency for indicated temperatures at 92.37% moisture content

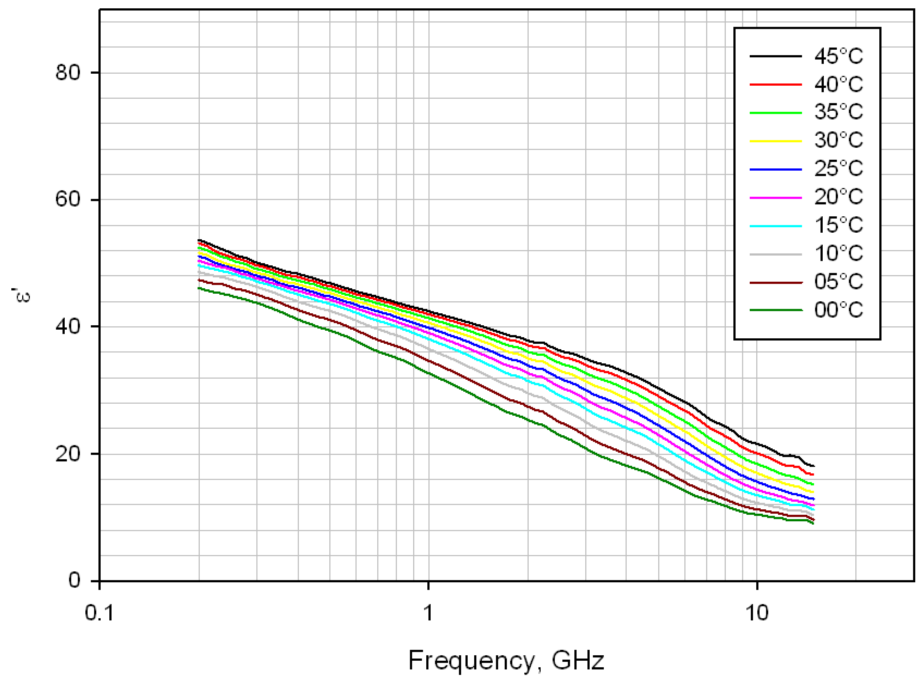

Figure 4.4 Measured dielectric constant as a function of frequency for indicated temperatures at 42.32% moisture content

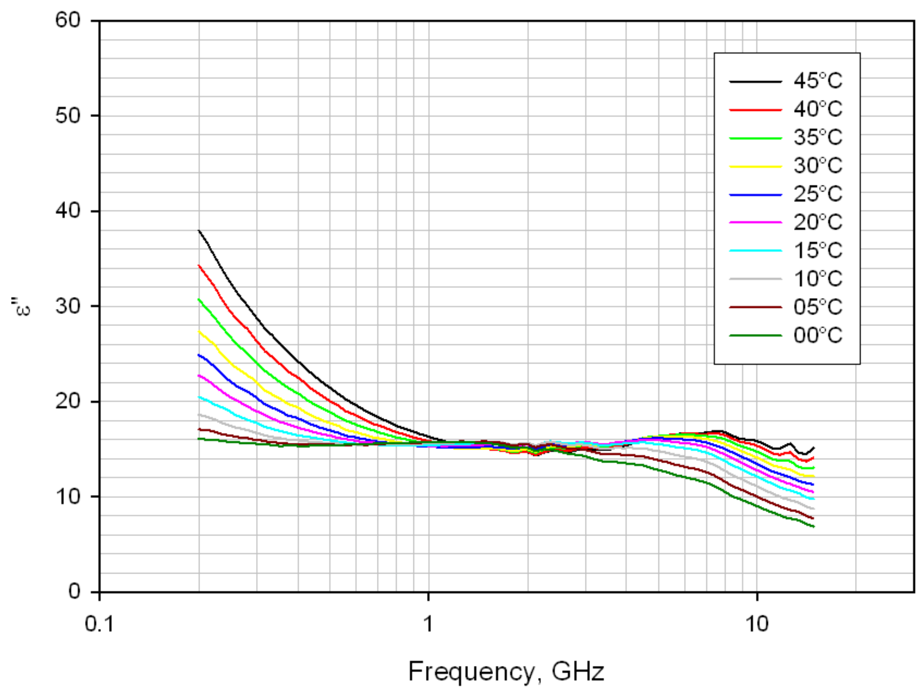

Figure 4.5 Measured dielectric loss factor as a function of frequency for indicated temperatures at 42.32% moisture content

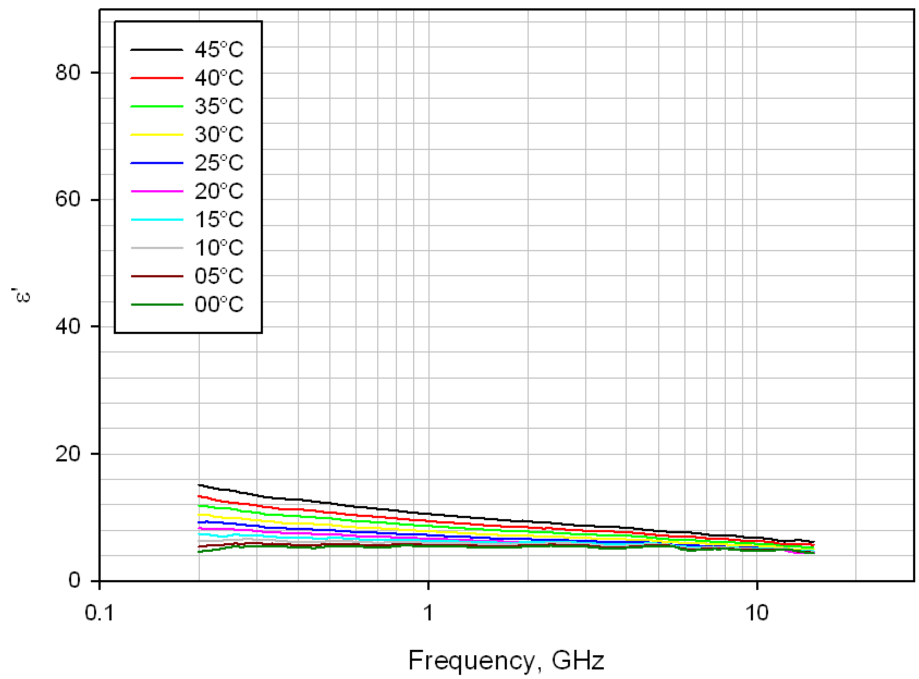

Figure 4.6 Measured dielectric constant as a function of frequency for indicated temperatures at 12.23% moisture content

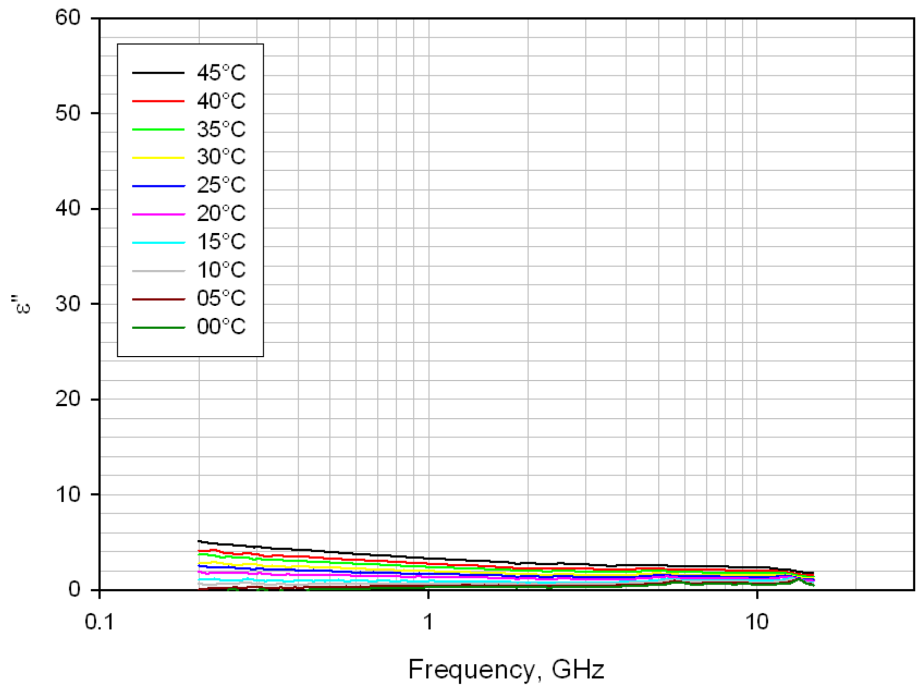

Figure 4.7 Measured dielectric loss factor as a function of frequency for indicated temperatures at 12.23% moisture content

Temperature and Moisture Dependence

To more closely examine the effects of temperature and moisture on the dielectric properties, three frequencies were selected. Two frequencies chosen, 2.46 GHz and 5.91 GHz, are close to established industrial, scientific, and medical (ISM) frequencies. The third frequency, 10.3 GHz, was chosen to analyze behavior of dielectric properties at higher frequencies.

Shown in Figures 4.8 and 4.9 are the changes in dielectric properties with temperature at 2.46 GHz. In Figure 4.8, the dielectric constant exhibits the most temperature-related variation in the critical moisture region of 30% to 50%. Below this region, the dielectric constant increases with temperature while, above this region the dielectric constant decreases with temperature. The dielectric loss factor has greater variation with temperature as moisture is increased. At lower moisture contents the dielectric loss factor increases with temperature as shown in Figure 4.9. Beyond approximately 50% moisture content the loss factor tends to decrease with temperature.

Figures 4.10 and 4.11 demonstrate the change in dielectric properties with temperature at 5.91 GHz. The temperature variation of the dielectric constant increases dramatically at approximately 30% as shown in Figure 4.10. The dielectric loss factor exhibits similar behavior however, there is also a noticeable shift in effect of temperature at higher moisture contents. In Figure 4.11 at moisture contents above 60%, the dielectric loss factor definitely decreases with increasing temperature.

Shown in Figures 4.12 and 4.13 are the changes in dielectric properties with temperature at 10.3 GHz. Here, the variation of the dielectric constant due to temperature changes increases with moisture as shown in Figure 4.12. The dielectric loss factor exhibits similar behavior with the exception that at moisture contents greater than 60% the loss factor decreases with temperature as shown in Figure 4.13. The effect of moisture on the temperature dependence of permittivity shows that its effect is proportional to the amount of moisture in the material. The fact that both the dielectric constant and the loss factor can either increase or decrease with temperature has been documented (Nelson 1973).

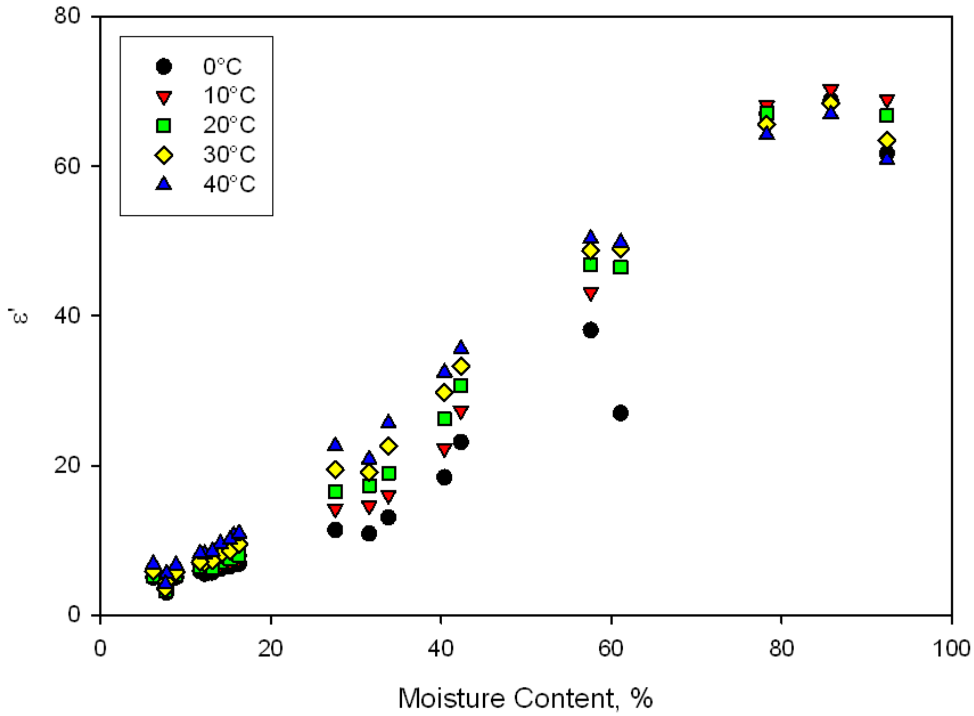

Figure 4.8 Dielectric constant as a function of moisture content at 2.46 GHz

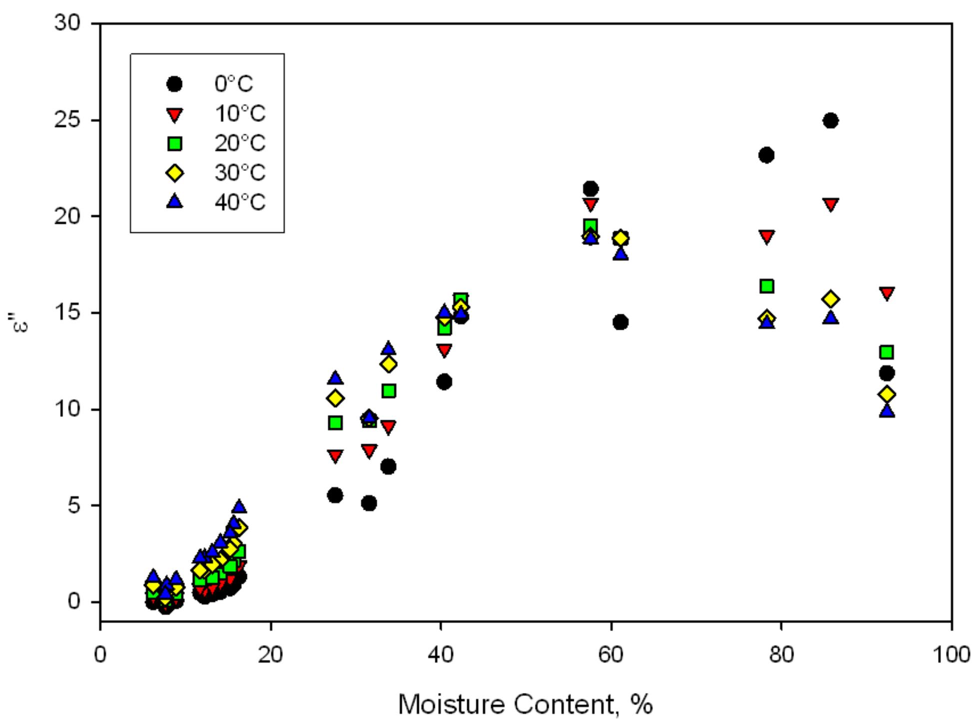

Figure 4.9 Dielectric loss factor as a function of moisture content at 2.46 GHz

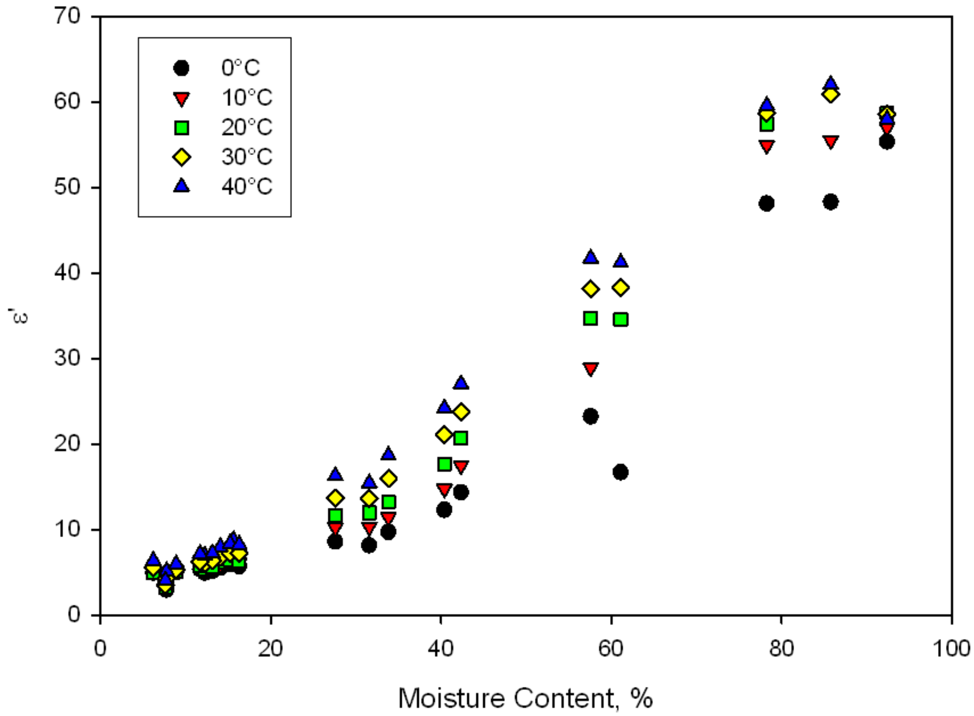

Figure 4.10 Dielectric constant as a function of moisture content at 5.91 GHz

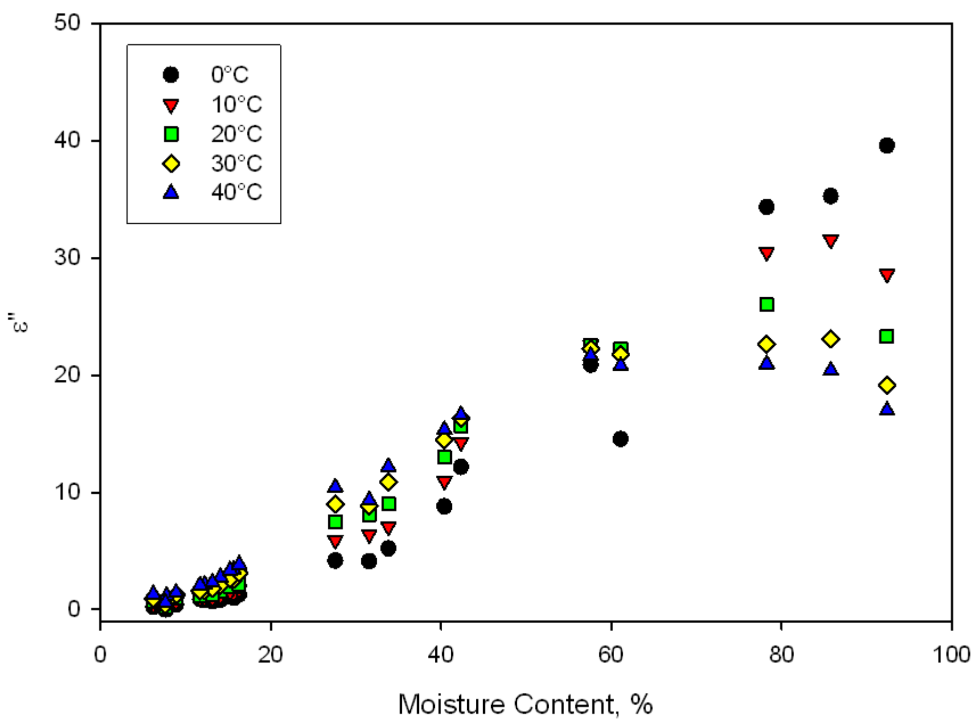

Figure 4.11 Dielectric loss factor as a function of moisture content at 5.91 GHz

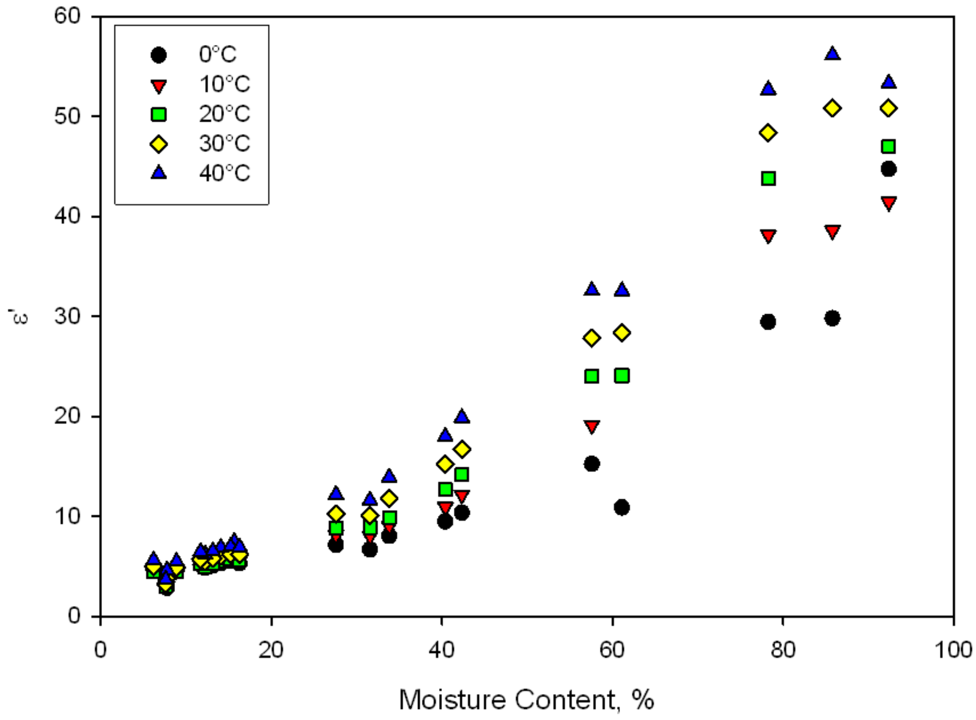

Figure 4.12 Dielectric loss factor as a function of moisture content at 10.3 GHz

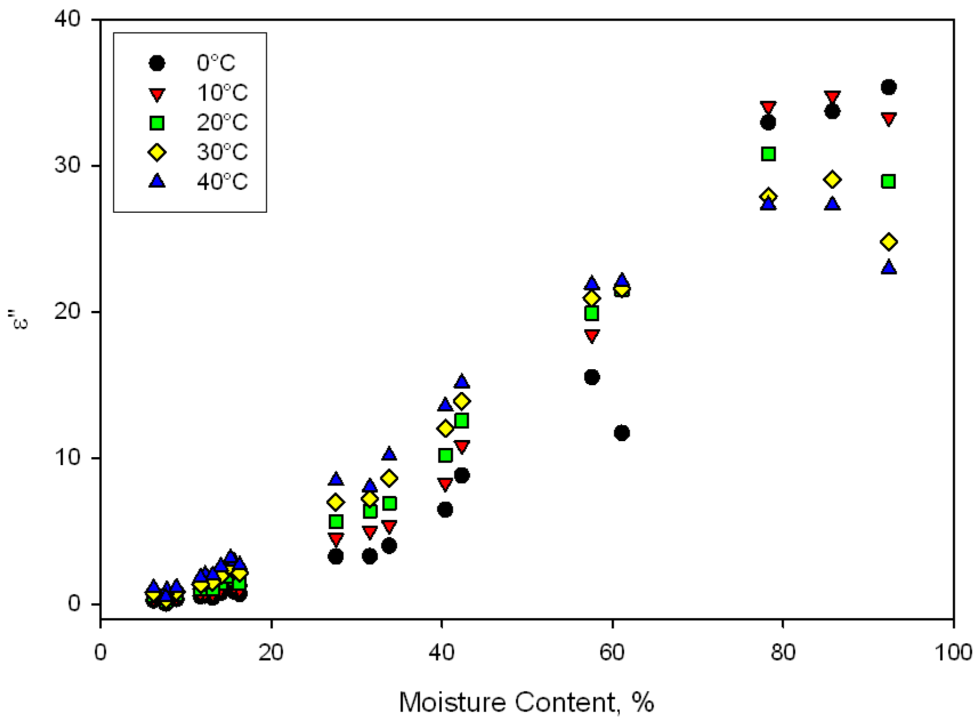

Figure 4.13 Dielectric loss factor as a function of moisture content at 10.3 GHz.

Temperature Compensation

At lower moisture contents, the effect of temperature is relatively constant across moistures. This offers an opportunity to design simple linear models to compensate for the effect of temperature. A modified ratio of the dielectric parameters was selected for use in this effort.

$$A_e = \frac{\varepsilon''}{\varepsilon' - 1} \tag{4.3}$$

This density-independent function, initially developed for particulate materials (Meyer and Schilz 1980), has been useful for moisture prediction in higher moisture biological materials (Shrestha and et al. 2005). Use of this function should minimize uncertainties in permittivity determinations due to unknown densities of minced onion samples for the dielectric probe measurements.

To avoid issues relating to the changing effects of temperature, the model developed focuses on the lower moisture region of minced onions. This region is where the endpoint for the curing of onions would most likely occur (Maw et al. 1997). Figures 4.14 to 4.16 show that a surface in three dimensions can be developed to compensate for the temperature effects for lower moisture contents at multiple frequencies as previously reported by Trabelsi (2001).

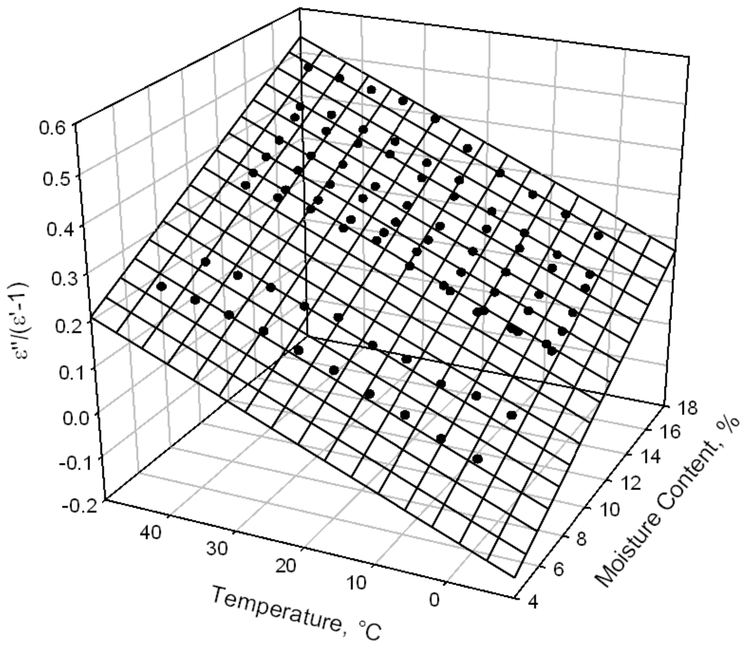

Figure 4.14 Three dimensional plane of moisture, temperature, and *ε''/(ε'-1)* at 2.47 GHz

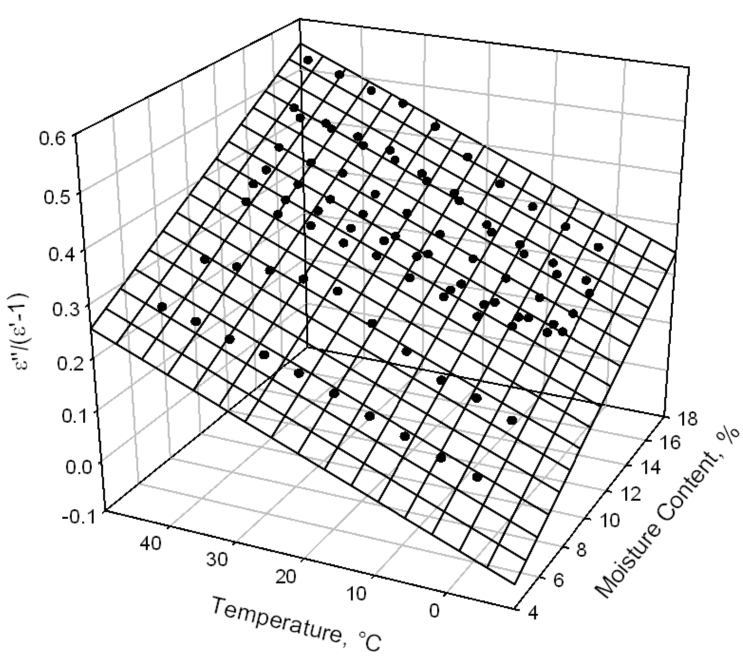

Figure 4.15 Three dimensional plane of moisture, temperature, and *ε''/(ε'-1)* at 5.91 GHz

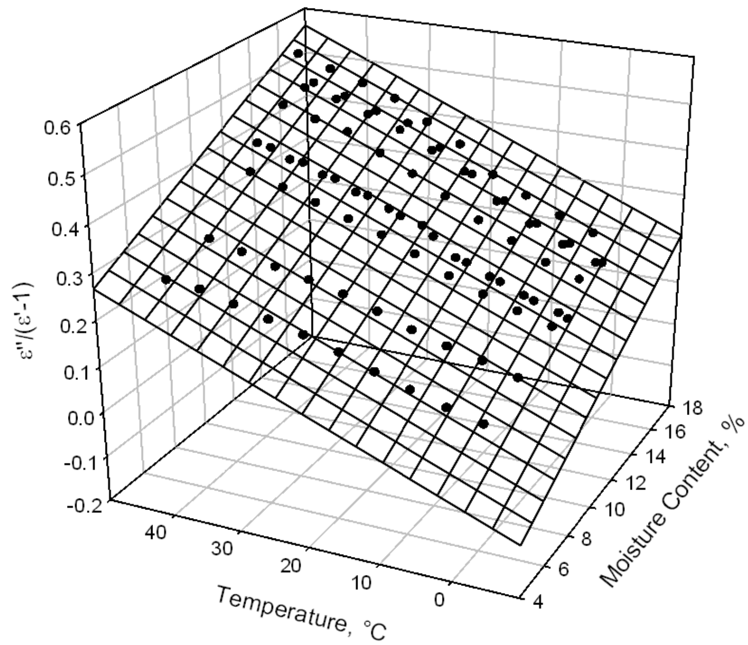

Figure 4.16 Three dimensional plane of moisture, temperature, and ε''/(ε'-1) at 10.3 GHz

The planes shown in Figures 4.14 through 4.16 demonstrate that temperature can be compensated for by using a multiple linear regression equation.

$$\frac{\varepsilon''}{\varepsilon'-1} = aM_{\%} + bT + c \tag{4.4}$$

A moisture content prediction equation is provided by solving equation (4.4) as follows:

$$M_{\%} = \frac{\frac{\varepsilon''}{\varepsilon'-1} - bT - c}{a} \tag{4.5}$$

where, $M_{\%}$ is the moisture content in percentage, T is the temperature in °C, and $a, b,$ and c are regression constants. The constants for these equations as well as the R^2 values are given in Table 4.1. The table shows the planes generated from dielectric properties of lower ranged frequencies have higher correlations with moisture content. Thus coefficients of determination increase with decreasing frequency.

Table 4.1 Regression constants and coefficients of determination for the temperature-corrected moisture prediction model of equation 4.5

Frequency	*a*	*b*	*c*	R^2
0.502 GHz	0.0275	0.0062	-0.2517	0.9360
1.03 GHz	0.0268	0.0060	-0.2393	0.9432
2.47 GHz	0.0234	0.0062	-0.1939	0.9288
5.91 GHz	0.0212	0.0052	-0.0906	0.9270
7.08 GHz	0.0195	0.0056	-0.0739	0.9096
10.3 GHz	0.0211	0.0060	-0.1164	0.8921
13.4 GHz	0.0175	0.0037	-0.0311	0.6586

Conclusions

The response of the dielectric properties to temperature changes can be compensated with a three-dimensional-surface model. The models developed utilize a density-independent function of the dielectric properties previously reported and work well for moisture contents between 6% and 16% at multiple frequencies. This moisture region was selected because of mixed response temperature change can have on the dielectric properties at higher moisture contents. Frequency-dependence analysis showed that dielectric properties undergo a shift in their response to temperature at frequencies between 1 GHz and 5 GHz. Above this frequency range, the dielectric constant increases with temperature at all moisture contents. The same conclusions cannot be stated for the dielectric loss factor because of the shift in the dielectric relaxation frequency. This frequency is a local maximum for the loss factor that gradually shifts towards higher frequencies with increasing moisture or temperature. This makes correcting for temperature in these regions more difficult. Thus, the temperature can be either directly or inversely related to dielectric properties, depending on the moisture content and the frequency range.

Temperature effects on measurement of the dielectric constant of minced onions are proportional to the amount of moisture in the material to begin with. Temperature- and moisture-dependence analysis showed that, while dielectric properties variation with temperature is constant at low moisture contents, after a certain point the variation increases with increasing moisture content. If a temperature-correction model were developed for higher moisture contents it should compensate for this increasing variation by making the temperature constant used in this equation proportional to the moisture content. However, this may increase the model uncertainty.

Findings of this research would be crucial in development of a sensor for testing the cure of Vidalia onions undergoing the curing process. Future work could investigate the development of temperature-correction models that operate in the broader ranges of moisture content and temperature. In addition, work could be started on towards the development of a new sensor that can make these measurements with inexpensive microwave components. Once implemented, a viable moisture sensing device has the potential to increase the efficiency and decrease the cost of the curing process.

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CHAPTER 5

CONCLUSIONS

In this study, dielectric spectroscopy was utilized to examine the potential for moisture prediction in Vidalia Onions. The advantage of this technique is that interaction of the electric field with the material can be explored efficiently over a broad frequency range. Through examination of the frequency spectrum tested, 200 MHz to 20 GHz in this case, an optimal frequency can be selected, and rigorously analyzed and tested for its suitability in prediction of quality parameters.

For moisture measurements at room temperature, the dielectric constant showed a nearly linear increase with moisture content at all frequencies. The dielectric loss factor behaves linearly only in the higher measured frequency ranges. This is due to the domination of dipole polarization at higher frequencies. The influence of ionic conduction, however, in contributing to the dielectric loss factor at lower measured frequencies clouds the response of this region for moisture prediction. Thus the cost of a future sensor, which generally increases with the frequency used, would have to be balanced with desired measurement accuracy.

At different temperatures, dielectric properties can behave differently depending on the temperature and moisture content. This behavior is the result of the change in the relaxation frequency of the tested material. Thus increases in temperature can potentially cause the dielectric properties to either increase or decrease depending on the frequency used. At and above the critical moisture content, with respect to bound and free water the effects of this behavior are more pronounced. Therefore, a straightforward linear temperature correction was used only in the low moisture region that contains the endpoint of the curing process.

Use of a density-independent function that employs a modified ratio of the dielectric constant and dielectric loss factor has the potential to reduce density-specific errors. Errors related to density variation can occur due to the difference in pressure applied with the probe or due to natural variations in the material itself. Since both the dielectric constant and dielectric loss factor are density-dependent, using a ratio of the dielectric properties results in a value that is density-independent. Use of this function enabled the prediction of moisture content with a high degree of accuracy up to the critical moisture content of about 40%. This function was also used in a temperature-correction model to correct for variations in the dielectric properties due to temperature in the low-moisture region.

This research would be central in the development of a sensor for testing the cure of Vidalia onions undergoing the curing process. The benefits of such a sensor can lead to increased control and optimization of the curing process of Vidalia onions. The curing of an onion is the most vital stage of processing to ensure that onions are sealed against the invasion of disease, rot, and further moisture loss. Currently this process is simply controlled by time, but year-to-year and crop-to-crop variations may render the time-controlled process inadequate. Curing represents an added cost in the production process in terms of energy and time. Additionally, overcuring Vidalia onions results in excess moisture loss that can affect the value of the product. Reductions of inadequate curing and costs associated excess moisture loss could benefit Vidalia onion producers.

Future work would be directed toward the development of a moisture sensor that can make these measurements without the need of a network analyzer. Ideally, the sensor would operate at a single frequency using inexpensive microwave components. The cheapest components would likely be found at ISM frequencies of 2.45, and 5.8 GHz. Thus, special attention was given to these frequencies in this research. Based on the results of this study, use of higher frequencies proved superior in moisture prediction at room temperature. However, lower frequencies performed better at temperature-compensated moisture prediction. Consideration would need to be taken as to the placement and setup of the moisture sensor in the curing process. Once implemented, however, potential exists for both cost savings, and reductions in crop losses.

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