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An Analysis upon Various Measurement Techniques of Dielectric Properties

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Abstract* – *The reasons for interest in the dielectric properties of materials are discussed. Terms are defined and principles involving dielectric properties of materials are summarized. Measurement techniques for determining dielectric properties of agricultural materials in the radio-frequency (RF) and microwave ranges are identified with reference citations given for detailed information. Finally, a few new potential applications for dielectric properties of materials are discussed and a few precautions are given for reliable determination of such properties by RF and microwave measurements.

The interest in dielectric properties of materials has historically been associated with the design of electrical equipment, where various dielectrics are used for insulating conductors and other components of electric equipment. Measurement of the bulk dielectric properties (dielectric constant, dielectric loss factor) is not an end unto itself. Rather, these properties are an intermediary vehicle for understanding, explaining, and empirically relating certain physico-chemical properties of the test material. Therefore, in this paper, an attempt is made to fully explore the existing knowledge of dielectric properties (complex permittivity), their role, and importance and the concept of various measurement methodologies and their development.

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INTRODUCTION

Dielectric properties of agricultural materials and products are finding increasing application as new technology is adapted for use in agriculture and related industries. The interest in dielectric properties of materials has historically been associated with the design of electrical equipment, where various dielectrics are used for insulating conductors and other components of electrical equipment. During much of the past century, materials research has provided many new dielectric materials for application in electronics. As the use of higher and higher frequencies came into practice, new materials, suitable for use in the radio-frequency, microwave, and millimeter wave regions of the electromagnetic spectrum, have been developed. The dielectric properties of these materials are important in the design of electrical and electronics equipment, and suitable techniques for measuring these properties for various applications have been developed as they were needed.

The interest in the dielectric properties of agricultural materials and products has been principally for describing the behavior of materials when subjected to high-frequency or microwave electric fields for dielectric heating applications and in their use for rapid methods of moisture content determination. The influence of the dielectric properties on the heating of materials by absorption of energy through radio-frequency dielectric heating, whether at high frequencies or microwave frequencies, has been well known for a long time, and many potential applications have been investigated. With the advent of commercial microwave heating and the wide acceptance of microwave ovens for the home, the concepts of dielectric heating have become much more widely appreciated.

The use of dielectric properties for measuring moisture content of products such as cereal grains has been recognized for at least 90 years and has been in common use for more than 50 years. However, the first dielectric properties for grain were not reported until 45 years ago.

Since then much data and information on the dielectric properties of grain and other agricultural products have become available, and the influence of important variables on these dielectric properties has been evaluated.

With the need for development of new sensing devices for the automation and control of various agricultural processes, there is a need for better understanding of the usefulness of dielectric properties of materials and methods for measuring these properties. Therefore, it is the purpose of this article to briefly summarize some of the measurement techniques with helpful comments and provide information related to some of their applications. Rather than explaining details of the various measurement techniques, readers are referred to appropriate sources for that information.

Dielectric materials play a key role in electronic circuits such as capacitors or insulators. Characterization of these materials in the early stage of development is essential to predict the performance of the final devices.

The electrical properties of a dielectric material are characterized by its complex permittivity. The real part of permittivity, also called dielectric constant, represents the material's ability to store energy when an external electric field is applied. Materials with a higher dielectric constant can store more energy in a small volume, while those with a lower value are preferred for signal transmission where minimum propagation delay is critical. The imaginary part of permittivity represents the loss dissipated in the material. Loss of material can lead to extra power consumption. It is possible to achieve various dielectric constants by controlling the micro structure of ceramics or nano composition of materials.

Dielectric measurement methods at frequencies below and above 10 GHz can also be based on the use of a microwave bulk resonator. Resonant measurement methods represent the most accurate way of obtaining dielectric constant and loss tangent with unclad thin materials, - which are just inserted inside the cavity. The high value of the unloaded quality factor 0 Q of the bulk resonator enables measurements of the smallest losses in the test materials. Potentially simple and reproducible test methods based on bulk resonator measurements have not, however, been accepted as industrial measurement tools, since most resonant techniques yield permittivity in the plane of the sample instead of the value of permittivity orthogonal to the surface of a thin substrate.

Measurement techniques which use dielectric split-cavity resonators are well established for measuring the parameters of thin dielectrics because of the inherently high values of their quality factors. For instance a cylindrical $H_{01\delta}$ H dielectric split resonator made from thermostable high permittivity ceramic has been successfully used for in-plane dielectric film measurements at frequencies below 10 GHz, but it was found unsuitable for measurements at higher frequencies due to increased loss tangent in ceramic materials. A fullmodel theory of split-cavity resonators including the effects of fringe fields at the gap in the cavity has been developed at NIST. Further details of this technique as well as of similar split-post dielectric resonator (SPDR) techniques for the measurement of in-plane properties of thin dielectric materials is available in NIST review papers.

Dielectric split-cavity resonators machined from sapphire can operate at much higher frequencies than those made from high permittivity ceramics. The sapphire disk "whispering gallery" (WG) resonator has a Q_0 about 40000 at room temperature for frequencies in the range of 40 GHz (wavelengthλ of about 8 mm). The typical diameter of a split-cavity sapphire resonator is about 1.5 λ . Such resonators have been proposed for measuring free dielectric films and have been successfully applied for the measurement of aluminium oxide film on aluminium substrates. There are two WG mode types: quasi- E (or HE) and quasi-H (or EH) with high a Q_0 for large azimuth mode index n >>1. They can be used for dielectric substrate measurements with orthogonal and tangential microwave E -fields respectively. In this paper we report on a successful project to measure the dielectric properties of thin films using the electric field component of an incident electromagnetic field which is orthogonal to the sample surface.

The only current standard methodology which makes possible measurements of dielectric properties of thin materials with the electric field component orthogonal to the sample surface is based on microstrip testing. As discussed above the microstrip method is labour intensive, requires considerable skill to implement and does not scale well above 10 GHz.

In contrast our technique can be easily scaled up for frequencies above 10 GHz. Our technique is particularly useful for measurements of microwave PCB materials, as there is no need for complex machining and no surface structures need be imaged. Because of its fundamental simplicity our method can be used non-destructively by relatively unskilled staff either in the laboratory or on the assembly line.

Also for the first time our test method allows the measurement of the effective microwave surface resistance of laminated metal at the interface between the laminated material and the dielectric material. The experimental values of surface resistance are important both for modelling the properties of integrated circuits and for qualifying particular PCB materials for high power applications.

A significant and universal problem with making dielectric measurements with an orthogonal field is the so-called "residual air-gap" which exists due to the micro-roughness at the contact between the flat resonator and the specimen surfaces. As a result an effective "residual air-gap" should be usually taken into consideration in the electrodynamic model of the measured structure.

MEASUREMENT PRINCIPLES AND TECHNIQUES

The measurement techniques appropriate for any particular application depend on the frequency of interest, the nature of the dielectric material to be measured, both physically and electrically, and the degree of accuracy required. Many different kinds of instruments can be used, but any measurement instrument that provides reliable determinations of the required electrical parameters involving the unknown material in the frequency range of interest can be considered.

For the radio frequencies, a material can be modeled electrically at any given frequency as a series or parallel equivalent circuit. Therefore, if one can measure the radiofrequency (RF) circuit parameters appropriately, the impedance or admittance for example, the dielectric properties of that material at that particular frequency can be determined from equations that properly relate the way in which the permittivity of the material affects those circuit parameters. The challenge in making accurate dielectric properties or permittivity measurements is in designing the material sample holder for those measurements and adequately modeling the circuit for reliable calculation of the permittivity from the electrical measurements.

Techniques for permittivity, or dielectric properties, measurements in the low-frequency medium-frequency, and high-frequency ranges were reviewed by Field (1954), including the use of various bridges and resonant circuits.

Dielectric properties of grain samples were determined from measurements with a precision bridge for audio frequencies from 250 Hz to 20 kHz with samples confined in a coaxial sample holder. At very low frequencies, attention must also be paid to electrode polarization phenomena which can invalidate measurement data, and the frequency below which this affects measurements depends on the nature and conductivity of the materials being measured.

A large amount of dielectric properties data were obtained in the 1- to 50-MHz range on grain and seed samples with a Q-Meter based on a series resonant circuit. Techniques were developed for higher frequency ranges with coaxial sample holders modeled as transmission-line sections with lumped parameters and measured with an RX-Meter for the 50- to 250-MHz range (Jorgensen et al., 1970) and for the 200- to 500-MHz, range measured with an Admittance Meter. Components of the sample holders used in the earlier studies with the RX Meter and Admittance Meter were assembled to provide a shielded open-circuit coaxial sample holder for grain, and a technique was developed for measurements from 100 kHz to 1 GHz with two impedance analyzers and use of proper calibrations and the invariance of-the-cross-ratio technique. The shielded open-circuit coaxial sample holder was also used by Bussey (1980) and by Jones et al. (1978) for determining dielectric properties of grain with highfrequency bridge measurements from 1 to 200 MHz.

A coaxial sample holder, designed to accommodate flowing grain, was modeled and characterized by full twoport scattering parameter measurements, with the use of several alcohols of known permittivities, and signal flow graph analysis to provide dielectric properties of grain over the range from 25 to 350 MHz.

For measurements at frequencies above those just mentioned, a number of microwave measurement techniques are available. At microwave frequencies, generally about 1 GHz and higher, transmission-line, resonant cavity, and free-space techniques have been useful. Principles and techniques of microwave dielectric properties measurements have been discussed in several reviews. Microwave dielectric properties measurement techniques can be classified as reflection or transmission measurements using resonant or nonresonant systems, with open or closed structures for the sensing of the properties of material samples. Closed-structure methods include waveguide and coaxial-line transmission measurements and short-circuited waveguide or coaxialline reflection measurements. Open-structure techniques include free-space transmission measurements and openended coaxial-line or open-ended waveguide measurements. Resonant structures can include either closed resonant cavities or open resonant structures operated as two-port devices for transmission measurements or as one-port devices for reflection measurements.

With the development of suitable equipment for timedomain measurements, techniques were developed for measuring dielectric properties of materials over wide ranges of frequency. Since modern microwave network analyzers have become available, the methods of obtaining dielectric properties over wide frequency ranges have become even more efficient. Extensive reviews have included methods for both frequency-domain and timedomain techniques.

Dielectric sample holder design for the specific materials is an important aspect of the measurement technique. The Roberts and von Hippel (1946) shortcircuited line technique for dielectric properties measurements provides a suitable method for many materials. For this method, the sample holder can be simply a short section of coaxial-line or rectangular-waveguide with a shorting plate or other short-circuit termination at the end of the line against which the sample rests. This is convenient for particulate samples, because the sample holder, and also the slotted line or slotted section to which the sample holder is connected can be mounted in a vertical orientation so the top surface of the sample can be maintained perpendicular to the axis of wave propagation as required for the measurement. The vertical orientation of the sample holder is also convenient for liquid or particulate materials when the measurements are taken with a network analyzer instead of a slotted line.

Dielectric properties of cereal grains, seed, and powdered or pulverized material have been determined with various microwave measurement systems assembled for such measurements. Twenty-one-mm, 50-Ω coaxialline systems were used for these measurements at frequencies from 1 to 5.5 GHz. A 54-mm, 50-Ω coaxial sample holder, designed for minimal reflections from the transition, was used with this same system for measurements on largerkernel cereals such as corn. A rectangular-waveguide X-band system was used to determine dielectric properties of grain and seed samples at 8 to 12 GHz. A rectangular waveguide K-band system was used for measurements on fruit and vegetable samples and on ground and pulverized materials for measurements at 22 GHz.

The choices of measurement technique, equipment, and sample holder design depend upon the dielectric materials to be measured, and the frequency or frequency range of interest. Vector network analyzers are expensive but very versatile and useful if studies are extensive. Scalar network analyzers and impedance analyzers are simpler and less expensive and can be appropriate for some programs. For limited studies, more commonly available microwave laboratory measurement equipment can suffice if suitable sample holders are constructed.

METHODS OF MEASUREMENT OF DIELECTRIC PROPERTIES

The measurement of dielectric properties has gained importance because it can be used for non-destructive monitoring of specific properties of materials undergoing physical or chemical changes. There are several techniques to measure the dielectric properties of agri-food materials. The dielectric properties of food materials in the microwave region can be determined by several methods using different microwave measuring sensors. The particular method used depends on the frequency range of interest and the type of target material. The choices of measurement equipment and sample holder design depend upon the dielectric materials to be measured, the extent of the research, available equipment, and resources for the studies. A Vector Network Analyzer (VNA) is expensive but very versatile and useful if studies are extensive. Scalar network analyzers and impedance analyzers are relatively less expensive but still too expensive for many programs. For limited studies, more commonly available radio frequency (RF) and microwave (MW) laboratory measurement equipment can suffice if suitable sample holders are constructed. Nyfors and Vainikainen (1999) gave four groups of measurement methods, namely, lumped circuit, resonator, transmission line, and free-space methods.

The lumped circuit techniques are no longer used to any great extent since they were only suitable for low frequencies and high loss materials. The latter three and the open-ended coaxial probe developed by Hewlett Packard employ impedance, spectrum, or network analyzers. Current developments are aimed at eliminating the need for these expensive yet versatile accessories.

MEASUREMENT PROCEDURE

The measurement setup includes a network analyzer, a software program that can be installed in the VNA or in a remote computer and the sample holder for the material under test. The network analyzers from Rohde & Schwarz such as the ZVx series can be used for the dielectric measurement. The network analyzer has a range of calibration methods to suit different measurement methods and allows for more accurate measurements. Other features such as time domain and embedding/de-embedding functions will enhance the accuracy of the measurement result of the MUT.

A function for direct extraction of the s-parameters is available in these series of network analyzers. It is very important to have this function because it facilitates the post processing of the s-parameters using some external software programs. The external programs are then used to convert the s-parameters to the permittivity and permeability parameters.

CONVERSION METHODS

There are various approaches for obtaining the permittivity and permeability from s-parameters. Table 1 gives an overview of the conversion methods utilizing various sets of s-parameters to determine the dielectric properties.

Conversion techniques	S-parameters	Dielectric properties
NRW	S11, S21, S12, S22 or S11, S21	ε_r, μ_r
NIST iterative	S11, S21, S12, S22 or S11, S21	ε_r, $\mu_r = 1$
New non-iterative	S11, S21, S12, S22 or S11, S21	ε_r, $\mu_r = 1$
SCL	S11	ε_r

Table 1 – Comparison between the conversion methods.

Each of the conversion method has different advantages and limitations. The selection of the method depends on several factors such as the measured s-parameters, sample length, the desired dielectric properties, speed of conversion and accuracies in the converted results.

Nicholson-Ross-Weir (NRW)- method provides a direct calculation of both the permittivity and permeability from the s-parameters. It is the most commonly used method for performing such conversion. Measurement of reflection coefficient and transmission coefficient requires all four (S_{11}, S_{21}, S_{12}, S_{22}) or a pair (S_{11}, S_{21}) of sparameters of the material under test to be measured. However, the method diverges for low loss materials at frequencies corresponding to integer multiples of one-half wavelength in the sample which is due to the phase ambiguity. Hence, it is restricted to optimum sample thickness of Og/4 and used preferably for short samples.

NIST Iterative- method performs the calculation using a Newton-Raphson's root finding method and is suitable for permittivity calculation only. It utilizes all four (S_{11}, S_{21}, S_{12}, S_{22}) or a pair (S_{11}, S_{21}) of s-parameters of MUT to calculate the reflection and transmission coefficient. It works well if a good initial guess is available. The method bypasses the inaccuracy peaks that exist in NRW method when the sample thickness is an integer multiple of one half wavelength (nOg/2). It is suitable for long samples and characterizing low loss materials.

New non-iterative- method is quite similar to the NRW method but with a different formulation and it is suitable for permittivity calculation for the case permeability <r = 1. It utilizes all four (S_{11}, S_{21}, S_{12}, S_{22}) s-parameters or just two (S_{11}, S_{21}) s-parameters of MUT to calculate the reflection and transmission coefficients. The method has the advantage of being stable over a whole range of frequencies for an arbitrary sample length. The method is based on a simplified version of NRW method and no divergence is observed at frequencies corresponding to multiples of one-half wavelength in the sample. It does not need an initial estimation of permittivity and can perform the calculation very fast. The accuracies are comparable to the iterative method. The method uses a partly different formulation from the NRW method and it can be easily extended to other measuring samples, for example micro-strip or coplanar lines. It also has the permittivity and permeability appear in the expression of the effective electromagnetic parameters. The effective electromagnetic parameters represent a propagation mode.

Short circuit line (SCL)- method is a one port measurement on coaxial lines or waveguides. It performs the calculation using the same Newton-Raphson's numerical approach as in the NIST iterative method and is suitable for permittivity calculation only. It utilizes only the S_{11} parameter of MUT to calculate the reflection coefficient. The method requires a good initial guess in order to obtain an accurate result. The method also requires the input of sample length and position for accurate measurements. The plot extracted from a technical note shows the permittivity obtained when using the SCL method.

CONCLUSION

In conclusion, the user needs to know the appropriate measurement and conversion methods for a material in order to measure its dielectric properties. It is necessary to use the right methods for the material to be measured because specific method is applicable to specific material. If the wrong methods are used, the measurement results will not be satisfactory. Advances in material science and process technologies have allowed for new devices through the development of new materials. Measurement systems with accuracy and stability are desired for time and cost effective evaluation.

The Parallel plate capacitance method is a standard technique for the evaluation of dielectric material. Fringe capacitance is a major source of errors and can be eliminated by using the appropriate fixture and/or software correction, which enables simple and repeatable measurements over a wide frequency range.

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