DETECTION OF IONIC CONDUCTIVITY AND MOISTURE CONTENT OF VARIOUS LIQUIDS USING MICROWAVE TECHNIQUE

MOHD AMIRUDDIN BIN ABD RAHMAN

FS 2011 99

DETECTION OF IONIC CONDUCTIVITY AND MOISTURE CONTENT OF VARIOUS LIQUIDS USING MICROWAVE TECHNIQUE

By

MOHD AMIRUDDIN BIN ABD RAHMAN

© COPYRIGHT UPM

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Master of Science

April 2011

To my lovely wife and kids
Siti Zaleha
Mohamad Amsyar Izzuddin
Sidratul Zahrah
Mohamad Aakif Hafizuddin

© COPYRIGHT UPM

Abstract of thesis submitted to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

DETECTION OF IONIC CONDUCTIVITY AND MOISTURE CONTENT OF VARIOUS LIQUIDS USING MICROWAVE TECHNIQUE

By

MOHD AMIRUDDIN BIN ABD RAHMAN

April 2011

Chairman: Professor Kaida Khalid, PhD

Faculty: Science

Measurement of ionic conductivity and moisture content of liquid is important because such information give indication about quality and also composition of elements of liquid. Previously microwave sensors are mainly used to determine moisture content in liquid. However, the microwave sensor may also be used to measure the conductivity at lower microwave frequency range. At present, detection of conductivity is done at low frequency and no previous efforts using microwave technique is considered because of the cost. However, a microwave system which could do simultaneous detection could overcome that problem.

A quasi-transverse electromagnetic technique employing variational method is used to simulate the behaviour of attenuated wave of the sensing element of the microwave microstrip sensor. Three different operating frequencies at 300 MHz, 2 GHz and 5 GHz is chosen particularly for detection of the attenuation of the sensor

© COPYRIGHT UPM

where the first two is for conductivity detection and the last is for moisture content detection. The calculated results demonstrate that the attenuation is a function of permittivity of liquid. Also, permittivity is related to the conductivity and moisture content of liquid at low and high frequency respectively. A computer program using Fortran programming language is used for the calculation.

The U-shaped microwave microstrip system is based on the transmission coefficient of the microstrip sensors. The system utilises two oscillators that act as the microwave source which operates at above mentioned frequencies. Two crystal detectors are placed in the system to measure input and output voltage so that total attenuation of the system can be determined. Conductivity and moisture content standard measurement are done using a commercial conductivity meter and oven drying method respectively.

Comparison of the insertion loss of the microstrip sensor system from calculation with attenuation of microstrip sensor alone shows excellent correlation of 0.9945. Established empirical relationship between insertion loss and conductivity at 300 MHz and 2 GHz gives correlation coefficient of 0.6334 and 0.9431 respectively. Another empirical relationship of insertion loss and moisture content at 5 GHz shows good fit at 0.9688. Evaluation of the measured conductivity and moisture content using developed system with standard measurement gives correlation coefficient of 0.3282 (300 MHz), 0.9435 (2 GHz), and 0.9781 (5 GHz). The main limitation of the developed system is in terms of measurement of conductivity of fresh latex samples

© COPYRIGHT UPM

PERPUSTAKAAN SULTAN ABDUL SAMAD
UNIVERSITI PUTRA MALAYSIA

at 300MHz since the variation of conductivity is less than 0.2 S/m. The moisture content measurement shows very good sensitivity at 1% change of moisture content.

The results present that the developed microwave system is possible to be used for simultaneous measurement of conductivity and moisture content of liquids. Further enhancement may be made to improve the resolution of conductivity measurement at low frequency. The system could be made portable which reliable for in-situ field-measurement.

© COPYRIGHT UPM

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENGESANAN SERENTAK KEBERALIRAN ION DAN KANDUNGAN LEMBAPAN PELBAGAI CECAIR MENGGUNAKAN TEKNIK GELOMBANG MIKRO

Oleh

MOHD AMIRUDDIN BIN ABD RAHMAN

April 2011

Pengerusi: Profesor Kaida Khalid, PhD

Fakulti: Sains

Pengukuran keberaliran ion dan kandungan lembapan penting kerana maklumat berkenaan memberikan petunjuk kepada kualiti dan kandungan unsur dalam cecair. Sebelum ini sensor gelombang mikro hanya digunakan kebanyakannya untuk menentukan kadar lembapan dalam cecair. Namun, sensor gelombang mikro boleh juga digunakan untuk mengukur keberaliran pada julat frekuensi rendah. Pada masa sekarang, keberaliran biasanya diukur pada julat frekuensi rendah gelombang mikro dan tiada usaha pada masa lalu menggunakan gelombang mikro untuk mengesan kekondusian ion disebabkan oleh kos. Walaubagaimanapun, satu sistem gelombang mikro yang boleh melakukan pengesanan serentak mampu mengatasi masalah tersebut.

© COPYRIGHT UPM

Satu teknik kuasi-elektromagnet lintang menggunakan kaedah bervariasi digunakan untuk menentukan pengecilan gelombang pada sensor mikrostrip. Tiga frekuensi pengendalian berbeza pada 300 MHz, 2 GHz, dan 5 GHz dipilih terutamanya untuk pengesanan pengecilan pada sensor dengan dua frekuensi pertama ialah untuk pengesanan keberaliran dan yang terakhir untuk pengesanan kandungan lembapan. Hasil pengiraan menunjukkan pengecilan gelombang bersandarkan kepada ketelusan yang berkait dengan keberaliran cecair pada frekuensi rendah dan kadar lembapan cecair pada frekuensi tinggi. Satu program komputer menggunakan bahasa pengaturcaraan Fortran digunakan untuk pengiraan.

Sistem sensor mikrostrip berbentuk U adalah berdasarkan kepada pekali penghantaran sensor. Sistem berkenaan menggunakan dua pengayun yang berfungsi sebagai sumber gelombang mikro beroperasi pada frekuensi yang dinyatakan di atas. Dua pengesan hablur diletakkan pada sistem untuk mengukur voltan input dan output yang membolehkan jumlah pengecilan sistem boleh ditentukan. Pengukuran keberaliran dan kandungan lembapan piawaian masing-masing dilakukan menggunakan meter keberaliran dan kaedah pengeringan ketuhar.

Perbandingan kehilangan sisipan sistem sensor mikrostrip dari pengiraan dengan nilai pengukuran pengecilan sensor tersebut menunjukkan korelasi yang sangat baik iaitu pada 0.9945. Hubungan emperik yang diuji di antara kehilangan sisipan dan keberaliran pada 300 MHz dan 2 GHz masing-masing memberikan pekali korelasi 0.6334 dan 0.9431. Seterusnya hubungan emperik di antara kehilangan sisipan dan

© COPYRIGHT UPM

kadar lembapan pada 5 GHz menunjukkan padanan yang baik pada 0.9688. Penilaian di antara keberaliran dan kadar lembapan yang diukur menggunakan sistem yang dibangunkan dengan pengukuran piawaian memberikan pekali korelasi 0.3282 (300 MHz), 0.9435 (2 GHz), dan 0.9781 (5 GHz). Kekangan utama menggunakan sistem yang dibangunkan ialah dari segi pengukuran keberaliran sampel susu getah segar pada frekuensi 300 MHz kerana perubahan keberaliran kurang daripada 0.2 S/m. Pengukuran kandungan lembapan menunjukkan kepekaan yang sangat baik iaitu pada 1% perubahan kandungan lembapan.

Hasil pengukuran menunjukkan sistem gelombang mikro yang dibangunkan sesuai untuk digunakan untuk pengukuran serentak keberaliran dan kadar lembapan cecair. Pembaikan seterusnya adalah dengan memperbaiki kejituan pengukuran keberaliran pada frekuensi rendah. Dengan ini, suatu sistem mudah alih boleh dibangunkan untuk pengukuran di lapangan.

© COPYRIGHT UPM

© COPYRIGHT UPM

ACKNOWLEDGEMENTS

Thank to God! Many people have helped me in succession of this project by supporting me with different level of assistance. I by my deepest gratitude would like to thank them for their contributions.

To my supervisory committee,

I would like to thank Professor Dr. Kaida Khalid and Associate Proffessor Dr. Jumiah Hassan for sharing their knowledge and giving me such wonderful guidance all the way in completing this project. Their advice and comments has been insightful to me.

To the technical support staff in Department of Physics,

I wish appreciation to all of them in terms of assisting me to perform experimental work. A special thank is due to, Mr. Mohd Roslim who shared his experience in fabricating microwave circuits and also helped me in using milling machine. Also to thank Mr. Hairi Mat for helping me with mechanical work in preparing the microwave sensor.

To my colleagues,

I enjoy amazing discussion with all of them especially with Ah Meng and Ashry. The core knowledge on microwave that we discussed is very valuable for me in understanding the topic. I appreciate their time to answer my questions.

Finally, thanks to my wife Siti Zaleha Mohamed Amin for her patience, love and moral guidance. Her tremendous support has succeeded me to complete this thesis.

TABLE OF CONTENTS

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

LIST OF TABLES

© COPYRIGHT UPM

LIST OF FIGURES

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

© COPYRIGHT UPM

LIST OF ABBREVIATIONS

TEM	Transverse Electromagnetic
PNA	Personal Network Analyzer
MIT	Massachusetts Institute of Technology
Q-factor	Quality Factor
RF	Radio Frequency
MRR	Microstrip Ring Resonator
VNA	Vector Network Analyzer
GPR	Ground Penetrating Radar
MC	Moisture Content
SMA	SubMiniature Version A
MUT	Material Under Test
ISO	International Organization of Standardization
ATSM	American Society for Testing and Materials
PNA	Personal Network Analyzer
PVC	Polyvinyl Chloride
VSWR	Voltage Signal Wave Ratio
DRO	Dielectric Resonator Oscillator

© COPYRIGHT UPM

VCO	Voltage Controlled Oscillator
LCD	Liquid Crystal Display

© COPYRIGHT UPM

CHAPTER 1

INTRODUCTION

1.1 Motivation of Project

Measurement of moisture content and electrical conductivity give information about water percentage and salt or ion content inside a material respectively. Quantifying water and salt content is a critical parameter in order to determine productivity, market value and quality indication of a product especially in agriculture industry. As example, most natural substances commercial values depending on their weight, hence the exact determination of moisture content will help to fix proper value of the product such as hevea rubber latex, milk, and grain. During transportation and storage of the product where a long term storage is free from microbial degradation. However, over drying grain can decrease its nutritional and reproductive values and contribute to the increased breakage during handling (Khalid, 2004). In terms of conductivity, it gives indication of water quality. In fruits production, conductivity is important tool to determine fruits maturity level (Guo et al., 2007). When crops are failing, conductivity relationship also may be studied to improve production.

Standard method to quantify conductivity and moisture content is using conductivity meter and oven drying method respectively. Currently, standard method to find conductivity is rapid. However, standard method to determine moisture content is time consuming. In addition to that, measurement of conductivity and moisture content simultaneously is impossible since the cost is high and the size of the

© COPYRIGHT UPM

hardware is not suitable for remote sensing. Hence there is a need for a device which is portable and has the ability to perform simultaneous sensing of conductivity and moisture content of materials.

In microwave region, electromagnetic wave is sensitive to ionic conductivity at its lower frequency counterpart and supplementary very strongly interacts with water molecules as frequency gets higher. As a result, dielectric properties of moist materials should have a good relationship with ionic conductivity at lower microwave frequency and moisture content at higher microwave frequency. Therefore microwave measurement technique could offer an attractive means to overcome above issue.

This research project is focused on providing answer whether simultaneous in-situ measurement of ionic conductivity and moisture content could be realized by implementing microwave sensor system.

1.2 Background of Project

The basic principle of microwave moisture measurement is interaction of biological materials with electromagnetic fields. At microwave frequency, when an electromagnetic wave passes a materials the wave is altered by the materials properties. Such properties include density, temperature, concentration, composition

© COPYRIGHT UPM

and microstructure of the material. The material properties obtained by this interaction is strictly described by two parameters namely, dielectric permittivity or also called dielectric properties, ε, and magnetic permeability, μ.

In this project, only non-magnetic liquid materials are tested which are saline water, seawater, concentrated latex and fresh latex. Indeed, most of the liquid substance on earth is also nonmagnetic. Thus microwave moisture measurement in this thesis will only be exploited by dielectric permittivity of materials.

Dielectric permittivity can be described in terms of dielectric constant and loss factor which is the real and imaginary part of complex permittivity respectively. Complex permittivity is generally expressed as following equation:

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

where ε^* is complex permittivity, ε' is dielectric constant, and ε'' is loss factor. Therefore, the term 'permittivity' and 'complex permittivity' are used interchangeably in this thesis.

At microwave frequency, only two physical mechanisms dominate materials dielectric behavior that is ionic conductivity and dipolar polarization. The terms mentioned here is further discussed in the next subsection.

Before that, the objective of this project was to design and develop a microwave microstrip sensor to characterize dielectric properties of liquid materials. Using the microstrip sensor configuration which was theoretically analyzed, a relationship of

© COPYRIGHT UPM

materials permittivity with both moisture content and conductivity could be experimentally verified. Microstrip is mainly chosen because the cost to produce is cheaper than other microwave sensors and could provide accurate and reliable readings. A brief introduction of microstrip sensor used to characterize the dielectric samples is also discussed in section 1.3.

1.2.1 Polarization

Polarization is defined as a phenomenon when an electric charge is distorted due to the force from applied electric field causing the charge slightly moved from its equilibrium position. Polarization can be divided into two processes which are called relaxation and resonant. There are four main types of polarization which are electronic polarization, atomic polarization, dipolar or orientation polarization and ionic polarization where the first two belongs to resonant and the latter belongs to relaxation. At different frequencies, the polarization mechanism affects the permittivity of materials differently as shown in Figure 1.1. Since only last two mechanisms are crucial at microwave frequency, the electronic and atomic polarization effect could be neglected since it is crucial only at infrared and optical frequencies respectively and is not discussed further.

© COPYRIGHT UPM

PERPUSTAKAAN SULTAN ABDUL SAMAD
UNIVERSITI PUTRA MALAYSIA

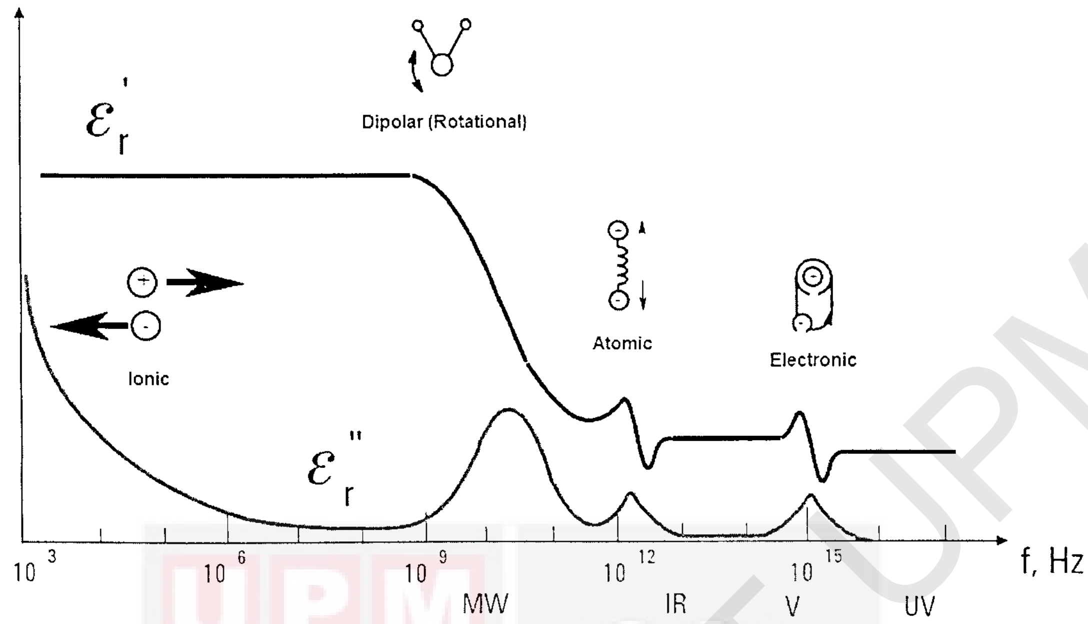

Figure 1.1. Polarization mechanisms at different frequency region. MW: Microwave, IR: Infrared, V: Visible, UV: Ultraviolet. (Source: "Basics of Measuring the Dielectric Properties of Materials," 2006)

Ionic polarization describes the ions conductivity in a medium. A material that has free charges suspended in non-conducting medium can be polarized when an electromagnetic field presents. The effect of ionic conductivity can only be seen in dielectric loss spectra. Only if heterogeneous materials which contains conducting region that is not in contact with each other presents, the influence of ion activity can be seen at the real part of permittivity, ε' (Hasted, 1973). The effect is called Maxwell-Wagner polarization. However, Maxwell-Wagner effect is negligible throughout this thesis since the moist materials used here are all homogeneous. Perhaps, most of macroscopic moist materials are homogeneous. In moist materials, ion conductivity dominates the low region of microwave frequency (usually less than 1GHz) (Kraszewski, 1996).

© COPYRIGHT UPM

Dipolar polarization is the dominant polarization at microwave frequency. When an electromagnetic field is applied to the medium, the force from the field makes the dipole molecules experience a torque. Consequently, the molecules rotate in line with the applied field where charge in the molecule is unevenly distributed. This phenomenon causes the molecule having a permanent dipole moment. At microwave frequency this phenomenon occurs at higher frequency range (usually above 1GHz). The whole relaxation process from ionic to dipolar polarizations is called dielectric relaxation. An example of the entire polarization process at microwave frequency region is shown in Figure 1.2.

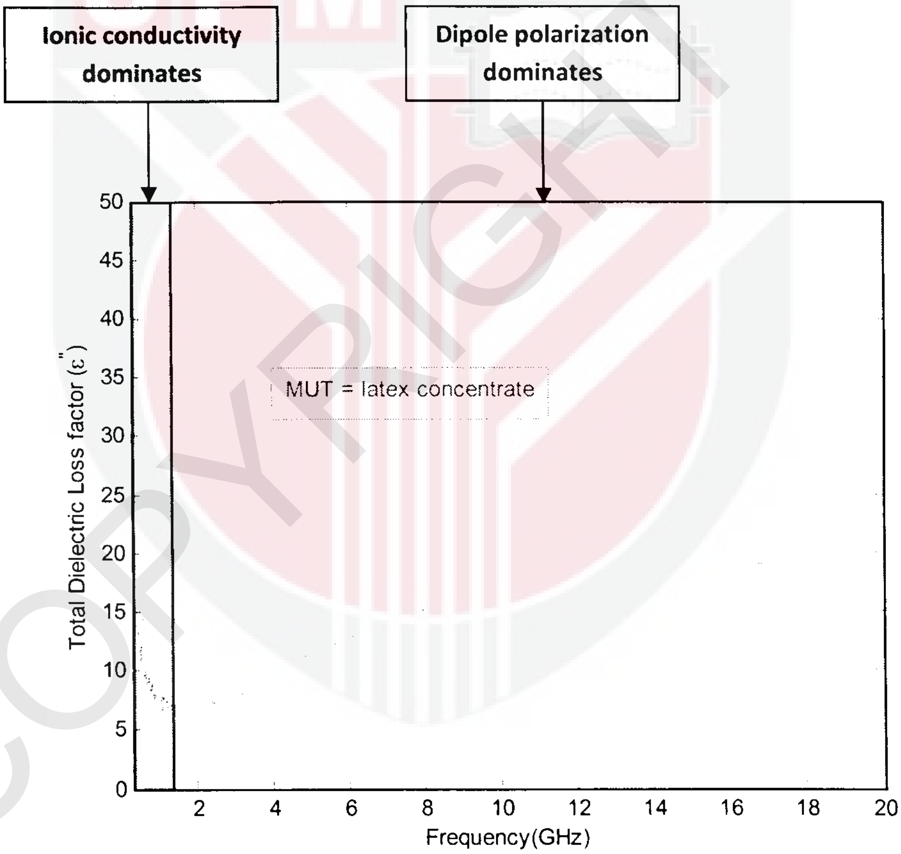

Figure 1.2. Effected of ionic conductivity and dipole polarization domination at microwave frequency region of concentrated latex sample.

© COPYRIGHT UPM

Each polarization mechanism affects the loss factor of complex permittivity of materials. For example if dipolar polarization is the only mechanism leading to losses, the complex permittivity could be written as:

$$\varepsilon_d^* = \varepsilon' - j\varepsilon_d'' \qquad (1.2)$$

where subscript d refers to loss due to dipolar polarization mechanism. However, overall loss of material can be defined as:

$$\varepsilon'' = \varepsilon_d'' + \varepsilon_e'' + \varepsilon_a'' + \varepsilon_i'' + \varepsilon_c'' \qquad (1.3)$$

where the subscript d, e, a and i refer to dipolar, electronic, atomic, and interfacial polarization and ε_c'' is loss due to ionic conductivity which is defined as:

$$\varepsilon_c'' = \frac{\sigma}{2\pi f \varepsilon_0} \qquad (1.4)$$

where σ is the ionic conductivity (S/m) and f is the operating frequency (Hz). However at microwave frequency, only ε_d'', and ε_c'' are considered and all of these losses are dependent of frequency, moisture content, and ionic conductivity. These dependencies are discussed further in the next subsections.

1.2.1.1 Operating frequency

Microwave region seems could be divided into three region of frequency. The first region is the region where the loss is dominated by Maxwell-Wagner polarization and ionic conductivity. In this region material having high ion concentrations will have high 'loss factor' due to those mechanism. The second region is where the effect of dipolar polarization can be seen. Here, water molecules slightly rotate due

© COPYRIGHT UPM

to dipolar polarization. At the same time, the mechanism occurs in the first region tend to decrease. Material 'loss factor' will have the lowest value in this region. The last region describes domination of dipolar polarization. At this range, the 'loss factor' due to dipolar polarization showing its peak at intermediate frequency and dielectric constant undergoes dispersion. This effect is called relaxation frequency.

When a measurement is made at certain range of frequencies, the best operating frequency needs to be chosen so that measured material permittivity is according to the objective. In this project, frequency of 300 MHz, 2 GHz and 5 GHz has been chosen as the operating frequencies of the developed microwave sensor system. The first two is used for conductivity detection and the last is for moisture content detection.

1.2.1.2 Moisture Content

Moisture content is defined as amount of water contains in a material. It is usually expressed in percentage. Conventional method that most commonly used is direct method such as oven drying and Karl-Fisher titration method. Oven drying method works by sample first is weighted to know the initial mass. Then the sample is dried in an oven having temperature at 70°C for about 18 to 24 hours to remove the water content before it is reweighted to determine the final mass.

Water in a sample of liquid may present in terms of bound and free water. Bound water has its molecules chemically combine with other molecules presence in the

© COPYRIGHT UPM

material or physically absorbed to the surface of material (Kraszewski, 1996). It is a fact that low concentration of liquid sample has high moisture content since there are less tightly bound water molecules. An example of relationship of moisture content with material permittivity is established as shown in Figure 1.3.

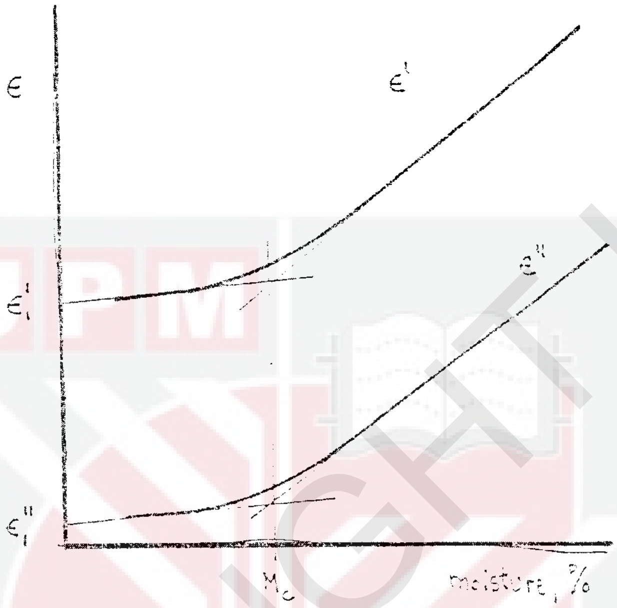

Figure 1.3. Material permittivity as a function of moisture content. (Source: Kraszewski, 1996)

1.2.2 Electrical Conductivity (Salt/Ion content)

Salt or ion content is measurable by electrical conductivity. Conductivity is a measure of how water can conduct electric current. Thus conductivity can only be measured when ions present. Standard method to measure conductivity is by having two parallel plates that is sandwiched within the sample which a low frequency potential is applied across the plates and the current is measured.

© COPYRIGHT UPM

1000730311

Ionic conductivity is extension of loss from imaginary part of complex permittivity function. The effect of conductivity can be seen at few megahertz of microwave frequency where the function of total dielectric loss is alike $1/f$ where f is the frequency of the propagating electromagnetic wave (Nyfors & Vainikainen, 1989). Dielectric loss due to ionic conductivity effect gets smaller and almost could not be seen as frequency gets into gigahertz range. This is because dipolar loss from water dominates the loss factor as frequency increases. Therefore, a good relationship of conductivity with material permittivity could only be established at megahertz range of microwave frequency for many materials.

1.3 Microwave Microstrip Sensor

Microstrip is a microwave planar transmission line having two conductors sandwiching a thin dielectric substrate as the geometry shown in Figure 1.4. The top conductor functions as a strip conducting line to propagate the wave and the bottom conductor acts as a ground. The wave propagation mode of microstrip line is quasi-transverse electromagnetic (quasi-TEM) (Figure 1.5). Microstrip line cannot support fully transverse electromagnetic (TEM) wave as the fields in not contained in single homogenous medium. Indeed, quasi-TEM is proposed because the some of the fields radiates in air which the phenomenon is called as fringing field. Since air and dielectric substrate have different dielectric constant, ε_r, another term describing dielectric constant for both medium is proposed which is called as effective dielectric

© COPYRIGHT UPM

constant, ε_{eff}. Information of ε_{eff} together with characteristic impedance of the line, Z_0 can be used to determine appropriate characteristic of microstrip geometry such as conductor strip width, w, and thickness of the substrate, d, as shown in Figure 1.4. It is also important to match Z_0 with line impedance to minimize the loss of transmitted signal. Details derivation and information of ε_{eff} and Z_0 is discussed in Chapter 3.

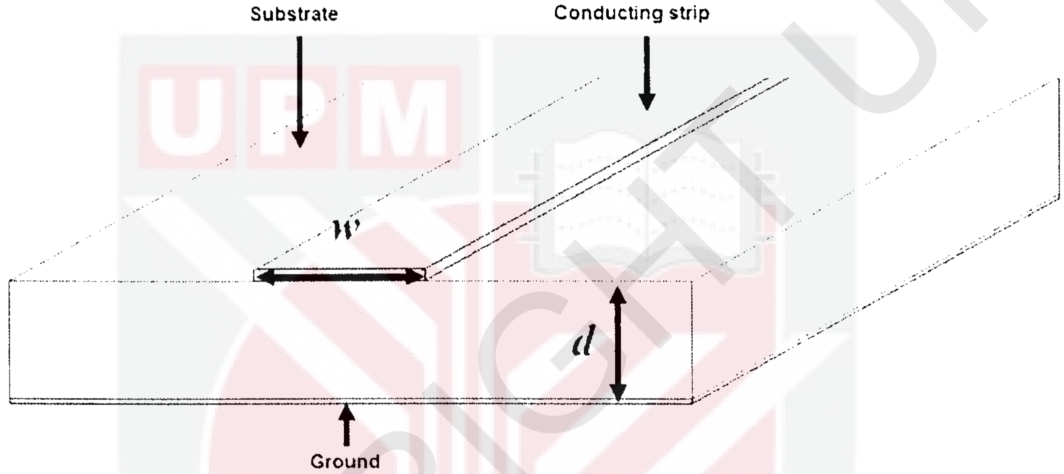

Figure 1.4. Geometry of microstrip transmission line.

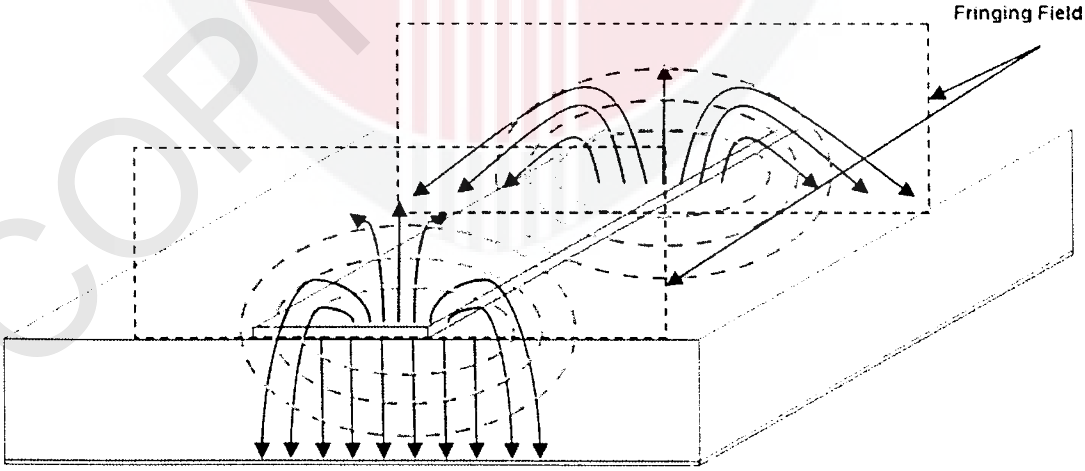

Figure 1.5. Electric (black line with arrow) and magnetic (red dashed line) fields of microstrip line with fringing field are shown.

© COPYRIGHT UPM

In material sensing, the sample is usually placed in contact with the conducting strip as shown in Figure 1.6. Previously it is imagined that part of the electromagnetic fields radiate in air, however now the fields radiate into the sample medium. The sample now also has different dielectric properties means that it has different ε_r than air which ε_r is equals to 1. Accordingly the ε_{eff} will always change whenever different moisture level of sample is placed on the microstrip line. Different values of ε_{eff} effect values of Z_0 as well. However, values of ε_{eff} and Z_0 only do not characterize a microstrip sensor completely, the length of the strip also must also be taken into consideration. As the principle of microwave microstrip sensor is described, it is important to know all of these parameters to design a good microstrip sensor.

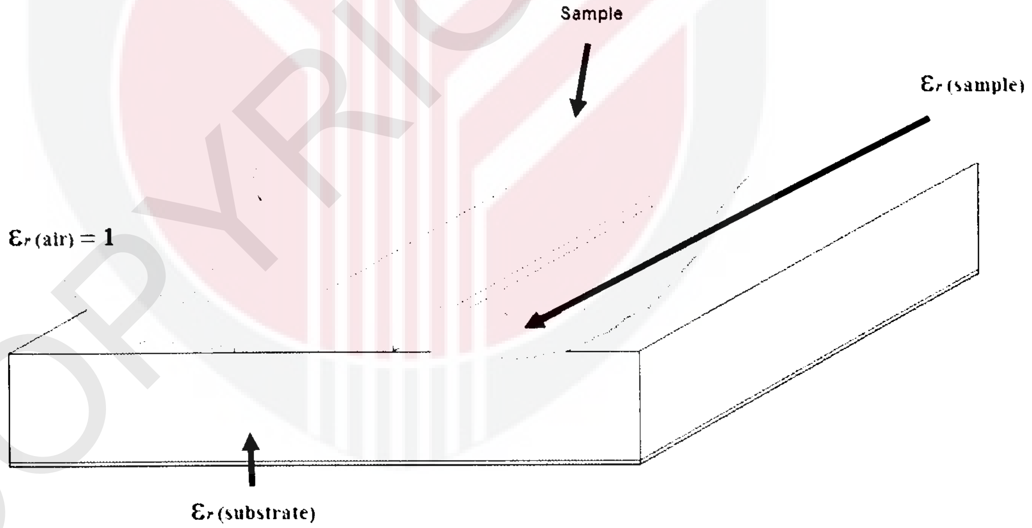

Figure 1.6. Example of measurement of materials with microstrip line sensor.

© COPYRIGHT UPM

1.4 Objectives

The main aim of this thesis is to demonstrate a microwave measurement system that could simultaneously measure ionic conductivity and moisture content of various liquid materials.

Specific aims of the project are given as follows:

1. To measure the dielectric properties of various concentration of concentrated latex, fresh latex, sea water and saline water to determine the suitable region for ionic conductivity and moisture content of materials

2. To develop a good approximation of theoretical model of the microstrip sensor and system which allows the dielectric properties of the samples to be deduced from the scattering parameters of the sensor

3. To design and fabricate planar U-shaped microstrip sensors to be integrated in the system and measure scattering parameters of the sensors using tested samples by Personal Network Analyzer (PNA) to determine the best frequency to be used in the microwave system

4. To develop, test and calibrate the microwave measurement system using mentioned samples to verify its accuracy and reliability compared to standard method measurement and also along with theoretical models and establish a

© COPYRIGHT UPM

relationship between microwave attenuation together with ionic conductivity and moisture content of the samples.

1.5 Overview of thesis

This thesis is organized into six chapters. Each of these chapters contains an independent introduction of the content and conclusion of the work in the end. The chapters present a complete and coherent story of the project done. First two chapters start with general idea and formulation of the problems. They provide project rationale and background, definitions to some related parameters which will be used extensively in the subsequent chapters and literature survey which address potential contribution in the area of microwave aquametry. The later chapters present thoroughly theoretical analysis of the sensor, development of prototype system and couple of important measurements methods. The last set of chapters then discuss significance of the results from the first two parts of the chapters and conclusions close the thesis.

Overview of the whole thesis is as follows:

Chapter 1 – Introduction

In current chapter, the aims, background and rationale of the research are presented. This chapter provides the basic impetus of the study and some relative definitions of

© COPYRIGHT UPM

microwave-based technique are presented. In addition, contributions made to the knowledge are highlighted.

Chapter 2 –Literature Review

In the second chapter, a general discussion and comparison of microwave aquametry technique and conductivity measurement are presented. Some important examples of previous applications of the technique are reviewed and summarized.

Chapter 3 – Quasi-TEM Analysis

In the third chapter, a thorough numerical model was developed to cater the parameters needed to design a transmission sensor utilizing planar microstrip line which is used in the microwave system. This chapter presents for the first time a numerical solution for the microstrip sensor which relates attenuation simultaneously with moisture content and conductivity.

Chapter 4 – Methodology

In the fourth chapter, the key discussion is about experimental work starting with development of the microwave system. Components build up the system are described in details. The system is the main measurement engine to monitor the liquid samples properties. Measurement of materials using high accuracy PNA to determine its complex permittivity is also mentioned as to support and provide comparison to data obtained from developed system.

© COPYRIGHT UPM

Chapter 5 – Results and discussion

In the fifth chapter, comparison and contrast of the theoretical attenuation data with experimental results are done. Limitation and errors of approximation of the chosen model is discussed.

Chapter 6 – Conclusion and Recommendation for Future Research

In the final chapter, a closing discussion and concluding remarks are presented. This section provides an overall discussion of the problem raised in the thesis and points to new issues and questions for future research as result of the thesis.

1.5 Summary of Original Work

The following is the summary of original contributions in this thesis:

1. Development of numerical algorithm for calculating initial estimate of the ionic conductivity of liquid materials.
2. Development of two microstrip sensors to avoid necessity to calibrate the system using water.
3. Analysis of simultaneous measurement of conductivity and moisture content of a microwave sensor system.

© COPYRIGHT UPM

© COPYRIGHT UPM

REFERENCES

Abbas, Z. (1994). *A Microstrip Sensor for Determination of Harvesting Time for Oil Palm Fruits.* Unpublished master thesis, Universiti Pertanian Malaysia, Malaysia.

Afsar, M. N., Birch, J. R., & Clarke, R. N. (1986). The measurement of the properties of materials. *Proceedings of the IEEE, 74*(1), 183-199.

Bahl, I. J., & Stuchly, S. S. (1980). Analysis of a Microstrip Covered with a Lossy Dielectric. *IEEE Transactions on Microwave Theory and Techniques, 28*(2), 104-109.

Basics of Measuring the Dielectric Properties of Materials. (2006). *Application Note*(Agilent Literature Number 5989-2589EN).

Calla, O. P. N., Bohra, D., Vyas, R., Purohit, B. S., Prasher, R., Loomba, A., et al. *Measurement of soil moisture using microwave radiometer.* International Conference on Recent Advances in Microwave Theory and Applications, 21-24 Nov. 2008, 2008.

Cataldo, A., Monti, G., De Benedetto, E., Cannazza, G., & Tarricone, L. (2009). A Noninvasive Resonance-Based Method for Moisture Content Evaluation Through Microstrip Antennas. *IEEE Transactions on Instrumentation and Measurement, 58*(5), 1420-1426.

Cownie, A., & Palmer, L. S. (1952). The Effect of Moisture on the Electrical Properties of Soil. *Proceedings of the Physical Society B, 65*, 295-301.

Fischer, M., Vainikainen, P., & Nyfors, E. *Dual-mode stripline resonator array for fast error compensated moisture mapping of paper web.* IEEE MTT-S International Microwave Symposium Digest, 8-10 May 1990, 1990.

Gagnadre, I., Gagnadre, C., & Fenelon, J. P. (1995). Circular patch antenna sensor for moisture content measurement on dielectric material. *Electronics Letters, 31*(14), 1167-1168.

Ghretli, M., Khalid, K., Grozescu, I. V., Sahri, H., & Abbas, Z. (2007a). Dual frequency microstrip antenna sensor for water content measurements independent of temperature variation. *Measurement Science and Technology, 18*, 1054.

Ghretli, M. M., Khalid, K., Grozescu, I. V., Sahri, M. H., & Abbas, Z. (2007b). Dual-Frequency Microwave Moisture Sensor Based on Circular Microstrip Antenna. *IEEE Sensors, 7*(12), 1749-1756.

Grant, E. H., Buchanan, T. J., & Cook, H. F. (1957). Dielectric behavior of water at microwave frequencies. *The Journal of Chemical Physics, 26*, 156.

Guo, W., Zhu, X., Nelson, S. O., Yue, R., Liu, H., & Liu, Y. (2010). Maturity effects on dielectric properties of apples from 10 to 4500 MHz. *LWT-Food Science and Technology*.

Guo, W. C., Nelson, S. O., Trabelsi, S., & Kays, S. J. (2007). Dielectric properties of honeydew melons and correlation with quality. *Journal of Microwave Power & Electromagnetic Energy, 41*(2), 48.

Hasted, J. B. (1973). *Aqueous dielectrics* (Vol. 17). London: Chapman and Hall London.

Horsfield, B. (2001). *The application of microwave sensing to the measurement of cheese curd moisture.* Unpublished doctoral dissertation, University of Southern Queensland, Australia.

Huang, J., Hussein, Z. A., & Petros, A. (2007). A VHF Microstrip Antenna With Wide-Bandwidth and Dual-Polarization for Sea Ice Thickness Measurement. *IEEE Transactions on Antennas and Propagation, 55*(10), 2718-2722.

Jacobsen, S. (1998). Reduction of hot spots in hyperthermia by means of broadband energy transmission. *Electronics Letters, 34*(20), 1901-1902.

Kaatze, U. (1997). The dielectric properties of water in its different states of interaction. *Journal of Solution Chemistry, 26*(11), 1049-1112.

Kent, M. (1972). The Use of Strip-Line Configuration in Microwave Moisture Measurements. *Journal of Microwave Power, 7*(3), 185-193.

Kent, M. (1973). The Use of Strip-Line Configuration in Microwave Moisture Measurements II. *Journal of Microwave Power, 8*(2), 189-194.

Kent, M., & Kohler, J. (1984). Broadband Measurment of Stripline Moisture Sensors. *Journal of Microwave Power, 19*(3), 173-179.

Kent, M., & Price, T. E. (1979). Compact Microstrip Sensor For High Moisture Content Materials. *Journal of Microwave Power, 14*(4), 363-365.

Khalid, K. (1986). *Analysis and Design of Microstrip and Coplanar Stripline Sensors.* Unpublished doctoral dissertation, University of Birmingham, United Kingdom.

Khalid, K. (2004). *Microwave Aquametry: A Growing Technology.* UPM Serdang: Bahagian Komunikasi Korporat, Universiti Putra Malaysia.

Khalid, K. B., Maclean, T. S., Razaz, M., & Webb, P. W. (1988). Analysis and optimal design of microstrip sensors. *IEE Proceedings. Part H. Microwaves, antennas and propagation, 135*(3), 187-195.

© COPYRIGHT UPM

© COPYRIGHT UPM

Kilic, B., & Madenci, E. (2010). An adaptive dynamic relaxation method for quasi-static simulations using the peridynamic theory. *Theoretical and Applied Fracture Mechanics, 53*(3), 194-204.

Kim, Y. I., Park, T. S., Kang, J. H., Lee, M. C., Kim, J. T., Park, J. H., et al. (2006). Biosensors for label free detection based on RF and MEMS technology. *Sensors and Actuators B: Chemical, 119*(2), 592-599.

Kona, K. S., & Rahmat-Samii, Y. *Dual-frequency dual-polarized sixteen-element stacked patch microstrip array antenna for soil moisture and sea surface salinity missions.* Antennas and Propagation Society International Symposium, 3-8 July 2005, IEEE 2005.

Kraszewski, A. (1980). Microwave Aquametry - A review. *Journal of Microwave Power, 15*(4), 12.

Kraszewski, A. (1996). *Microwave aquametry: electromagnetic wave interaction with water-containing materials*. New York: IEEE PRESS.

Kraszewski, A. W. (1991). Microwave aquametry-needs and perspectives. *IEEE Transactions on Microwave Theory and Techniques, 39*(5), 828-835.

Kraszewski, A., Kulinski, S., & Matuszewski, M. (1976). Dielectric properties and a model of biphase water suspension at 9.4 GHz. *Journal of Applied Physics, 47*(4), 1275-1277.

Kraszewski, A., Trabelsi, S., & Nelson, S. O. (2002). Broadband Microwave Wheat Permittivity Measurements In Free Space. [Journal]. *Journal of Microwave Power & Electromagnetic Energy, 37*(1), 41-54.

Kraszewski, A. W., & Nelson, S. O. (2004). Microwave permittivity determination in agricultural products. *Journal of Microwave Power & Electromagnetic Energy, 39*(1), 41.

Lasne, Y., Paillou, P., Freeman, A., Farr, T., McDonald, K. C., Ruffie, G., et al. (2008). Effect of Salinity on the Dielectric Properties of Geological Materials: Implication for Soil Moisture Detection by Means of Radar Remote Sensing. *IEEE Transactions on Geoscience and Remote Sensing, 46*(6), 1674-1688.

Liskow, C. L. (1948). Ultra high frequency apparatus for inspection of sheet and other materials: US Patent 2,457,695.

Mane, V., & Puri, V. (2009). Response of Ag thick film microstrip equilateral triangular patch antenna to overlay of moisture laden soybean. *Microelectronics International, 26*(3), 56-59.

McLaughlin, D. J., McIntosh, R. E., Pazmany, A., Hevizi, L., & Boltniew, E. (1991). A C-band scatterometer for remote sensing the air-sea interface. *IEEE Transactions on Geoscience and Remote Sensing, 29*(2), 260-267.

McLaughlin, D. J., Pazmany, A. L., Boltniew, E., Hevizi, L. G., & McIntosh, R. E. *An Airborne C-band Scatterometer For Remote Sensing The Air-sea Interface.* International Geoscience and Remote Sensing Symposium (IGARSS), 10-14 Jul 1989, 1989.

Nortemann, K., Hilland, J., & Kaatze, U. (1997). Dielectric Properties of Aqueous NaCl Solutions at Microwave Frequencies. *The Journal of Physical Chemistry A, 101*(37), 6864-6869.

Nyfors, E., & Vainikainen, P. (1989). *Industrial microwave sensors* (Vol. 9). Norwood: Artech House, Inc.

Okamura, S. I. (2000). Microwave technology for moisture measurement. *Subsurface Sensing Technologies and Applications, 1*(2), 205-227.

Oliner, A. A. (1984). Historical Perspectives on Microwave Field Theory. *IEEE Transactions on Microwave Theory Techniques, 32*, 1022-1045.

Palmer, L. S., & Forrester, G. R. (1941). A reflection method of measuring optical and electrical constants at ultra-high radio frequencies. *Proceedings of the Physical Society, 53*, 479.

Peplinski, N. R., Ulaby, F. T., & Dobson, M. C. (1995). Dielectric properties of soils in the 0.3-1.3-GHz range. *IEEE Transactions on Geoscience and Remote Sensing, 33*(3), 803-807.

Piscarreta, D., & Kam-Weng, T. *Miniaturized microstrip square loop resonator probe for solution sensing.* Asia-Pacific Microwave Conference Proceedings (APMC), 4-7 Dec. 2005, 2005.

Pozar, D. M. (2005). Microwave Engineering, 3rd: John Wiley & Sons, Hoboken, NJ, USA.

Sarabandi, K., & Li, E. S. *Characterization of soil moisture using a microstrip resonator.* International Geoscience and Remote Sensing Symposium (IGARSS) Surface and Atmospheric Remote Sensing: Technologies, Data Analysis and Interpretation., 8-12 Aug 1994, 1994.

Sosa-Morales, M. E., Tiwari, G., Wang, S., Tang, J., Garcia, H. S., & Lopez-Malo, A. (2009). Dielectric heating as a potential post-harvest treatment of disinfesting mangoes, Part I: Relation between dielectric properties and ripening. *Biosystems Engineering, 103*(3), 297-303.

© COPYRIGHT UPM

Stuchly, M. A., Kraszewski, A., Stuchly, S. S., & Smith, A. M. (1982). Dielectric properties of animal tissues in vivo at radio and microwave frequencies: comparison between species. *Physics in Medicine and Biology, 27*, 927-936.

Svacina, J. (1992). Analysis of multilayer microstrip lines by a conformal mapping method. *IEEE Transactions on Microwave Theory and Techniques, 40*(4), 769-772.

van Wieringen, N., Wiersma, J., Zum Vörde Sive Vörding, P., Oldenborg, S., Gelvich, E. A., Mazokhin, V. N., et al. (2009). Characteristics and performance evaluation of the capacitive Contact Flexible Microstrip Applicator operating at 70 MHz for external hyperthermia. *International Journal of Hyperthermia, 25*(7), 542-553.

Windle, J. J., & Shaw, T. M. (1956). Dielectric Properties of Wool Water Systems. II. 26 000 Megacycles. *The Journal of Chemical Physics, 25*, 435.

Wu, T. T. (1957). Theory of the Microstrip. *Journal of Applied Physics, 28*, 299-302.

Verma, A. K., & Bhupal, A. (1998). Dielectric loss of multilayer microstrip line. *Microwave and Optical Technology Letters, 17*(6), 368-370.

Yamashita, E. (1968). Variational Method for the Analysis of Microstrip-Like Transmission Lines. *IEEE Transactions on Microwave Theory and Techniques, 16*(8), 529-535.

Yamashita, E., & Mittra, R. (1968). Variational Method for the Analysis of Microstrip Lines. *IEEE Transactions onMicrowave Theory and Techniques, 16*(4), 251-256.

Yogi, R. A., Gangal, S. A., Aiyer, R. C., & Karekar, R. N. (1998). Microwave ring resonator as a novel bio-material moisture sensor. *Sensors and Actuators B: Chemical, 50*(1), 38-44.

Zhang, Y., & Okamura, S. (2006). A Density-Independent Method for High Moisture Content Measurement Using a Microstrip Transmission Line. *Journal of Microwave Power & Electromagnetic Energy, 40*(2), 110-118.

Zhen-Qi, H., Xing-Tong, C., Shi-Lu, T., & Xiao-Yan, H. (2008). The penetration and measurement of GPR microwave on reclaimed soil moisture under constrained condition. *International Journal of Mining, Reclamation and Environment, 22*(3), 179-193.

© COPYRIGHT UPM