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DEVELOPMENT OF A MICROCONTROLLER-BASED MICROWAVE INSTRUMENTATION SYSTEM FOR DETERMINATION OF MOISTURE CONTENT IN OIL PALM FRUITS AND GINGER

NUR BIHA BINTI MOHAMED NAFIS

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By

NUR BIHA BINTI MOHAMED NAFIS

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

January 2018

DEDICATION

Special thanks:

To my beloved Father, Mother, Siblings and Friends.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

DEVELOPMENT OF A MICROCONTROLLER-BASED MICROWAVE INSTRUMENTATION SYSTEM FOR DETERMINATION OF MOISTURE CONTENT IN OIL PALM FRUITS AND GINGER

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January 2018

Chair: Associate Prof. Zulkifly Abbas, PhD
Faculty: Science

In agriculture, moisture content (MC) is among the important factors that are closely correlated to the properties of agriculture products. There is a diverse range of techniques such as Near-Infrared (NIR) spectroscopy, magnetic resonance, X-ray and computed tomography that have been used for the quality assessment in agriculture products. However, the microwave aquametry technique which applies MC measurement and correlates it to the quality of the agriculture products, has been widely used due to the fast, precise, cost and energy saving as well as compliance with safety regulations. Several sensors such as, microstrip and coplanar which are based on the attenuation measurement, have been suggested previously for the MC determination but these techniques required laborious preparation. The Keysight OEC probe has been used to determine the permittivity of agriculture products, however, it requires a network analyzer which is bulky and expensive. As a solution to this limitation, the low cost microcontroller-based microwave instrumentation system for determination of MC percentage in oil palm fruits and gingers is developed in order to determine the quality of samples by relying on MC measurement. This thesis describes in detail the development of a microcontroller-based microwave instrumentation system for the determination of MC percentage in oil palm fruits and ginger to determine the quality of samples by relying on MC measurement. This instrumentation system or also known as reflectometer operates at 2GHz includes a stripline directional coupler, two diode detectors, a PIC microcontroller, liquid crystal display (LCD), and sensors such as open ended coaxial-stub contact panel and monopole sensors. The stripline directional coupler's design, analysis and also performance testing are accomplished by using Microwave Office Software. The Flow Code version 5.5 was used to program the PIC16F690 microcontroller for data acquisition as well as to calculate the MC based on measured reflected voltage, processing and LCD display. The permittivity measurement is carried by using the Keysight 85070B dielectric probe kit that utilize with the computer controlled HP 8720B vector network analyzer software. The COMSOL Multiphysics® software is used to visualization of the electric field distribution of both the open ended coaxial-stub contact panel and monopole sensors based on the permittivity value measured. The calibration equations relating the measured reflected voltage by using the reflectometer to the actual MC, and permittivity (dielectric constant (ε′) and loss factor (ε")) has been established. The predicted percentage of MC in samples is calculated based on the measured reflected voltages can by interchanging the y and x axes. On the other hand, for the predicted permittivity measurement, the calibration equation between the reflected voltage and MC is substituted into the relationship between permittivity and MC. The accuracies of the calibration equations were determined by comparing the predicted MC with the actual MC using microwave oven drying method on another batch of the samples while for the permittivity measurement, the accuracy is determined by comparing the predicted and actual permittivity values that obtained from the another batch of permittivity measurement by using Keysight OEC probe. All of the calibration equations shows a good agreement for input reflected voltage which utilizing the reflected voltage values to determine the MC, ε′ and ε" by utilizing the mean relative error formula. For oil palm fruits, the accuracies for MC, ε′ and ε" were within 3.8%, 4.1%, and 4.5%, respectively. While for ginger, the accuracies for MC, ε′ and ε" were within 2.9%, 2.7%, and 3.6%, respectively.

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

PEMBANGUNAN SISTEM INSTRUMENTASI MIKROGELOMBANG BERASASKAN MIKROPENGAWAL UNTUK MENENTUKAN KANDUNGAN LEMBAPAN DALAM BUAH KELAPA SAWIT DAN HALIA

Oleh

NUR BIHA BINTI MOHAMED NAFIS

Januari 2018

Pengerusi: Prof. Madya Zulkifly Abbas, PhD
Fakulti: Sains

Dalam pertanian, kandungan lembapan (MC) adalah antara faktor penting yang berkaitan rapat dengan sifat produk pertanian tersebut. Terdapat pelbagai teknik seperti spektroskopi Near-Infrared (NIR), resonans magnetik, sinar-X dan tomografi yang telah digunakan untuk penilaian kualiti dalam produk pertanian. Walau bagaimanapun, teknik gelombang mikro akuametri dengan menggunakan pengukuran MC yang boleh dikaitkan dengan kualiti produk pertanian telah digunakan secara meluas kerana teknik ini cepat, tepat dan juga penjimatan kos dan tenaga yang mematuhi peraturan keselamatan. Beberapa sensor seperti microstrip dan coplanar yang berdasarkan pengukuran pelemahan telah dicadangkan sebelum ini untuk penentuan MC tetapi teknik ini memerlukan persediaan yang sukar. Penggunaan Keysight OEC dalam menentukan ukuran ketelusan produk pertanian berdasarkan pengukuran MC di dalam sampel. Bagaimanapun, penggunaan Keysight OEC memerlukan penganalisis rangkaian yang besar dan mahal. Sebagai penyelesaian kepada had ini, sistem instrumentasi gelombang mikro berasaskan mikrokontroler kos rendah untuk menentukan peratusan MC dalam buah kelapa sawit dan ginger untuk menentukan kualiti sampel dengan bergantung pada pengukuran MC. Tesis ini menerangkan secara terperinci pembangunan sistem instrumentasi gelombang mikro berasaskan mikrokontroler untuk menentukan peratusan MC dalam buah kelapa sawit dan halia untuk menentukan kualiti sampel dengan bergantung kepada ukuran MC. Sistem instrumentasi atau lebih dikenali sebangai meter pantulan mikrogelombang beroperasi pada 2 GHz ini terdiri daripada satu pengandingan arah garis lucutan, dua pengesan diod, mikropengawal PIC, paparan kristal cecair (LCD), dan sensor seperti sensor panel perhubungan sepaksi koaksial terbuka dan sensor monopole. Reka bentuk, analisa dan juga ujian prestasi pengandingan arah garis lucutan dicapai dengan menggunakan perisian “Microwave Office”. Perisian “Flowcode” versi 5.5 telah digunakan untuk memprogramkan mikrokontroler PIC16F690 untuk pengumpulan data serta mengira kandungan kelembapan berdasarkan voltan yang dipantulkan, pemprosesan dan paparan LCD. Pengukuran ketelusan dilakukan dengan menggunakan kit penyelidikan dielektrik

Keysight 85070B yang digunakan sekali dengan perisian penganalisis rangkaian vektor HP 8720B yang dikawal komputer. Perisian COMSOL Multiphysics® digunakan untuk menvisualisasikan pengedaran medan elektrik kedua-dua panel sensor panel perhubungan sepaksi koaksial terbuka dan sensor monopole berdasarkan nilai ketelusan yang diukur. Persamaan penentukuran yang berkaitan dengan voltan yang dipantulkan yang diukur dengan menggunakan reflectometer dengan MC sebenar, dan ketelusan (pemalar dielektrik (ε′) dan faktor kehilangan (ε")) telah diadakan. Ramalan peratusan MC dalam sampel boleh dikira berdasarkan voltan pantulan yang diukur dengan menukar paksi y dan x. Selain itu, untuk pengukuran ketelusan yang diramalkan, persamaan penentukuran antara voltan yang dipantul dan kandungan kelembapan diganti ke dalam hubungan antara ketelusan dan MC. Ketepatan persamaan penentukuran ditentukan dengan membandingkan MC yang diramalkan dengan MC sebenar menggunakan kaedah pengeringan ketuhar micro gelombang dengan menggunakan kumpulan sampel yang berbeza manakala untuk ukuran ketelusan, ketepatan ditentukan dengan membandingkan nilai ketelusan yang diramalkan dan sebenar yang diperolehi dari satu lagi pengukuran ketelusan dengan menggunakan Keysight OEC. Semua persamaan penentukuran menunjukkan perjanjian yang baik untuk input voltan yang dipantulkan yang menggunakan nilai voltan yang dipantulkan untuk menentukan MC, ε′ dan ε" dengan menggunakan rumusan ralat relatif min. Bagi buah kelapa sawit, ketepatan untuk MC, ε′ dan ε" berada dalam 3.8%, 4.1 %, dan 4.5%, manakala bagi halia, ketepatan bagi MC, ε′ dan ε" masing-masing adalah 2.9%, 2.7% dan 3.6%.

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I certify that a Thesis Examination Committee has met on 19 January 2018 to conduct the final examination of Nur Biha binti Mohamed Nafis on her thesis entitled "Development of a Microcontroller-Based Microwave Instrumentation System for Determination of Moisture Content in Oil Palm Fruits and Ginger" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

Chen Soo Kien, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Siti Khairunniza binti Bejo, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Mohd Fadzil bin Ain, PhD
Professor Ir.
Universiti Sains Malaysia
Malaysia
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 28 March 2018

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Zulkifly Abbas, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Jumiah Hassan, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD
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TABLE OF CONTENTS

Page

ABSTRACT i
ABSTRAK iii
ACKNOWLEDGEMENTS v
APPROVAL vi
DECLARATION viii
LIST OF TABLES xiii
LIST OF FIGURES xiv
LIST OF ABBREVIATIONS xvii

CHAPTER

1 **INTRODUCTION** 1
  1.1 Microwave Aquametry 2
    1.1.1 Microwave Sensors 2
    1.1.2 Open Ended Coaxial Sensor 3
    1.1.3 Complex Permittivity 4
  1.2 Problem Statement 5
  1.3 Research Objectives 6
  1.4 Thesis Layout 6

2 **LITERATURE REVIEW** 8
  2.1 Techniques for Moisture Content Determination of Agricultural Products 8
    2.1.1 Open Sun Drying Technique 8
    2.1.2 Oven Drying Technique 9
    2.1.3 Microwave Oven Drying Technique 9
  2.2 Microwave Moisture Measurement Method 10
    2.2.1 Rectangular Dielectric Waveguide Method 10
    2.2.2 Open Ended Coaxial (OEC) Method 11
    2.2.3 Monopole Sensor Method 13
  2.3 Basic of Microwave-Material Interaction 14
  2.4 Oil Palm Fruit 16
    2.4.1 An Overview of the Oil Palm Fruit 16
    2.4.2 Oil Palm Fruits Morphology 17
    2.4.3 Ripeness Techniques in Oil Palm Fruit 18
  2.5 Ginger 21
    2.5.1 An Overview of Ginger 21
    2.5.2 Ginger Morphology 22
    2.5.3 Post harvest of ginger 23
  2.6 Stripline Versus Microstrip 24

3 **THEORY** 26
  3.1 Stripline Impedance Formulation 26
    3.1.1 Linear Stripline 26
    3.1.2 Stripline's Width Equation 27

3.1.3 Attenuation of Stripline 27
3.1.4 Coupled Stripline 29
3.1.5 Coupler Stripline’s Synthesis Equations 29
3.1.6 Attenuation of Coupler Stripline 30
3.2 Stripline Impedance Analysis 30
3.2.1 Variation in Characteristic Impedance with Substrate’s Permittivity, Normalized Thickness and Width 30
3.2.2 The Optimum Parameters of 50Ω Characteristic Impedance Stripline 32
3.2.3 Attenuation of Stripline 33
3.2.4 Maximum Frequency Operation for Single TEM Stripline 35
3.2.5 Variation in Even and Odd Mode Characteristic Impedance of the Coupled Stripline 36
3.2.6 Optimum Values of W/b and S/b for Coupled Stripline 39
3.2.7 Attenuation of Coupled Stripline 41
3.3 Theory of Open Ended Coaxial Sensor 41
3.3.1 Admittance Model 41
3.3.2 FEM Formulations and Implementations 42

4 **METHODOLOGY** 46
4.1 Sample Preparation and Measurement of Moisture Content 46
4.2 Complex Permittivity Measurement 48
4.3 Reflectometer 49
4.3.1 Measurement setup 49
4.3.2 Directional Coupler Circuit Layout and Simulation Using Microwave Office 52
4.3.3 Performance Testing of Stripline Directional Coupler 53
4.3.4 Fabrication of Directional coupler 55
4.3.5 Development of a Data Acquisition Program for the Reflectometer by using Flowcode Software 56
4.4 FEM Techniques for COMSOL Multiphysics procedure 58

5 **RESULT AND DISCUSSION** 65
5.1 The Permittivity of Standard Materials 65
5.2 Ginger 66
5.2.1 Variation in Dielectric Properties of Ginger with Frequency for Different Percentage of MC 66
5.2.2 Variation in Complex Permittivity of Ginger with Different Percentage of MC at Selected Frequencies 68
5.2.3 Calibration Equation to Determine the MC 71

from Measured Permitittivity
5.2.4 The Effect Of Percentage of MC in Ginger on Electric Field Distribution 71
5.2.5 Calibration Equation to Determine the MC and Permitittivity based on the Measured Reflected Voltage at 2 GHz 73
5.2.6 Performance Analysis OEC-SCP sensor 76
5.3 Oil palm fruits 77
5.3.1 Variation in Complex Permittivity of Oil Palm Fruit with Frequency for Different Percentage of Moisture Content 77
5.3.2 Variation in Permittivity of Oil Palm Fruit with Different Percentage of MC at Selected Frequencies 79
5.3.3 Calibration Equation to Determine the MC from Measured Permitittivity 85
5.3.4 The Visualization of Effect Electric Field Distribution due to the Effects of MC Percentage in Oil Palm Fruit 85
5.3.5 Calibration Equation to Determine the MC and Permittivity based on the Measured reflected voltage at 2GHz 88
5.3.6 Performance Analysis of Monopole Sensor 89

6 CONCLUSION AND SUGGESTIONS 91
6.1 Conclusion 91
6.1.1 Main Contributions 92
6.2 Recommendations for Future Work 92

REFERENCES 94
APPENDICES 104
BIODATA OF STUDENT 108
PUBLICATIONS 109

LIST OF TABLES

Table		Page
2.1	Comparison between open sun drying, oven drying, and microwave oven drying	10
2.2	Comparison between RDWG, Agilent 85070B dielectric probe, OEC and monopole sensor	14
2.3	The composition of ginger as approaching maturity	22
3.1	Variation of W/b for 50Ω characteristic impedance of stripline of different t/b and ε_r	33
3.2	Values of parameters W/b and S/b of 50Ω coupled stripline for different types of RTDuriod substrate at selected coupling values	40
4.1	Comparison for S-parameter of stripline directional coupler	54
4.2	The dimension defined of monopole sensor in 2D work-plane	60
4.3	The geometrical parameter when the monopole sensor extruded to 3D work-plane	60
4.4	The properties of subdomain settings	62
4.5	Boundary settings	62
5.1	Measurement of permittivity of water and PTFE at 25°C for several selected frequencies by using Keysight OEC probe	65
5.2	The relationship between ε' and ε'' of Ginger with MC at selected frequencies	70
5.3	The sensitivity of (a) ε' and (b) ε'' against MC in ginger	70
5.4	Accuracy of prediction equation when compared to standard oven drying method	71
5.5	The relationship between ε' with MC at various selected frequencies	81
5.6	The sensitivity of ε' against MC in oil palm fruits	81
5.7	The relationship between ε'' with MC at various selected frequency	84
5.8	The sensitivity of ε'' against MC in oil palm fruits	84
5.9	Accuracy of prediction equation when compared to standard oven drying method	85

LIST OF FIGURES

Figure **Page**

1.1 The sample measurement setup for OEC line sensor 4
2.1 The experimental setup for RDWG method 11
2.2 MC measurement procedure of a MUT using an OEC sensor 11
2.3 The comparison in fringing field between an OEC sensor (left) with a monopole sensor (right) 12
2.4 The structure of monopole sensor with radius and length of protruding inner conductor a and h, respectively 13
2.5 The water's relative permittivity values 15
2.6 Variation in permittivity with increasing frequency for potato 16
2.7 The oil palm fruit morphology 17
2.8 The categories of oil palm fruit. (a) Dura; (b) Tenera and (c) Pisifera 17
2.9 A tenera bunch 18
2.10 Variation in MC and oil content with weeks after anthesis 19
2.11 The relationship between water content and oil content in fruit mesocarp 20
2.12 A ginger morphology 23
3.1 Stripline 26
3.2 Coupled stripline 29
3.3 Relationship between stripline's characteristic Impedance with W/b for variation of t/b: (a)RTDuriod5870, (b)RTDuriod6006,(c) RTDuriod6010 31
3.4 Variation in W/b of stripline with ε_r For various conductor thickness 32
3.5 The variation of attenuation with frequency for different substrate's thickness; (a) RTDuriod5870, (b)RTDuriod6006, (c) RTDuriod6010. 34
3.6 Cut off frequency for stripline at 50Ω characteristic impedance 36
3.7 The effect of coupling on characteristics impedance of coupled stripline 37
3.8 The characteristic impedance for coupled stripline with variation of W/b and S/b parameters; (a)RTDuriod5870, (b) RTDuriod6006, (c) RTDuriod6010 38
3.9 Optimum of (a) W/b and (b) S/b of 5038Ω characteristic impedance for various coupling and ε_r. 39
3.10 The attenuation for 50Ω characteristic impedance with 20dB coupling of coupled stripline 41
3.11 Types of finite element in the FEM: (a) three node triangular, (b) four node tetrahedron and (c) eight node hexahedron 43
3.12 The discretization of an arbitrary solution region with triangular elements. 43
4.1 Flowchart of methodology 46

4.2 Sample preparation for (a) ginger and (b) oil palm fruit 47
4.3 Electronic weight balance 47
4.4 Permittivity measurement setup with Keysight OEC probe 49
4.5 Permittivity measurement setup when the Keysight OEC probe loaded with the samples 49
4.6 Reflectometer;(a) block diagram,(b) Measurement setup, (c) OEC–SCP sensor, (d) monopole sensor,(e) Reflection measurement of the sensors loaded with both samples 50
4.7 Designed of stripline directional coupler using MWO: (a) schematic diagram and (b)design layout 53
4.8 S-parameter simulation (MWO) for 50Ω characteristic impedance of stripline directional coupler 54
4.9 Fabrication procedure of the reflectometer circuit 55
4.10 Fabricated stripline directional coupler 56
4.11 Flowcode software; (a) Graphical programming and (b) Panel view 58
4.12 COMSOL’s procedure for FEM calculation 59
4.13 Model Navigator dialog box 59
4.14 The geometrical dimension of monopole sensor in: (a) 2D work plane and (b) 3D work 60
4.15 The boundary surrounding the sensor geometry when attached with the sample 61
4.16 The subdomain settings dialog box 61
4.17 Boundary Settings dialog box 62
4.18 The far field defined for the sample’s wall in the Boundary Settings dialog box 63
4.19 Normal mesh size discretized sensor geometry 63
4.20 The field distribution of the unloaded (a) monopole and (b) OEC-SCP sensors at 2GHz 64
5.1 Variation of complex permittivity with frequency for water and PTFE when measured by using Keysight OEC probe 66
5.2 (a) ε’ and (b) ε’’ of Ginger with frequency at various percentages of MC 67
5.3 The relationship between pH and various percentage of MC 68
5.4 The relationship between MC and (a) ε’ and (b) ε’’ of ginger various selected frequencies 69
5.5 The electric field distribution surrounding the OEC–SCP sensor inside Ginger of variation of percentage of MC 72
5.6 Variation in reflected voltage with MC with of the OEC-SCP: (a) 30%-90%MC, (b) 40% -80%MC 74
5.7 Variation in (a) ε’ and (b) ε’’ with MC 75
5.8 Comparison between measured and actual (a) MC (b) ε’ and (c) ε’’ 76
5.9 The relationship of (a) ε’ and (b) ε’’ with frequency for variation percentage of MC 78
5.10 The relationship between ε’ and MC of oil palm fruit within range frequencies 1 GHz to 4 GHz. 79
5.11 The relationship between ε” and MC of oil palm fruit within range frequencies 1 GHz to 4 GHz. 82
5.12 The electric field distribution of monopole sensor for oil 86

palm fruits at different percentage of MC
5.13 Variation in RV with MC at frequency of 2 GHz 88
5.14 The Relationship between Actual MC and Predicted MC 89

LIST OF ABBREVATIONS

MC	Moisture content
NIR	Near-infrared
MUT	Material under test
Keysight OEC probe	Keysight 85070e dielectric probe kit
OEC	Open ended coaxial
ε^*	Complex dielectric permittivity
ε'	Dielectric constant
ε''	Loss factor
C	Static capacitance
OEC-SCP	Ended coaxial - stub contact panel
LCD	Liquid crystal display
FEM	Finite element method
VNA	Vector network analyzer
T	Sample thickness
$\lvert\varepsilon\rvert$	Expected complex permittivity
KF	Karl Fischer
IR	Infrared
PTH	Plated through hole
Z_o	Characteristic impedance
ε_r	Substrate's permittivity
b	Substrate's thickness
W	Conductor's width
t	Conductor's thickness
L	Line length
ρ	Metal bulk resistivity normalize to gold
α_T	Total loss of stripline
α_c	Conductor loss
α_d	Dielectric loss
f_T	Cut-off frequency
R_s	Sheet resistivity
$tan\delta$	Loss tangent
Z_{oe}	Characteristic impedance of even mode
Z_{oo}	Characteristic impedance of odd mode
C	Coupling factor
S	Separation between parallel coupler lines
$\tilde{Y}$	Normalized admittance
Γ	Reflection coefficient
$G(0)/Y_o$	Normalized conductance
$B(0)/Y_o$	Susceptance
ε_c	Dielectric constant of the material filling the coaxial line
a	Inner radius
b	Outer radius
k_o	Free space propagation constant
J_o	Bessel function of zeroth order
Si	Sine integral
V	Potential
N	Number of elements (noes)

V_e	Element potential typically approximated with polynomial equation
n	The number of nodes
α_i	The element shape function
V_{ei}	Potential at node *i*
$C_{ij}^{(e)}$	Element coefficient matrix
f	Node with free potentials
p	Node with predetermined potentials
$[K]$	Sparse matrix
$[b]$	Excitation matrix
m_w	Mass before drying
m_d	Mass after drying
NaOH	Caustic soda
$FeCI_3$	Ferric chloride
LCD	Liquid crystal display panel
PTFE	Polytetrafluoroethylene
UV	Ultraviolet
$\sim.dfx$	Drawing exchange format
MWO	Microwave office
SMA	Sub-miniature a
ε'_{water}	Dielectric constant of water
ε''_{water}	Loss factor of water
pH	Potential of hydrogen
ε_o	Permittivity of free space
σ	Conductivity
f	Frequency
TEM	Transverse electromagnetic
PCB	Printed circuit board

CHAPTER 1

INTRODUCTION

The attention of using the microwave instrument in agriculture has risen rapidly nowadays. These microwave instrument has provided new methods for characterization of food properties in order to determine the precise harvest time, perform rapid measurement of certain products' quality, and determine the condition of various points in processing and storage operations. In Malaysia, the application of microwave instrumentation systems in agriculture is still new compared to infrared, laser, ultrasound, electrical capacitance. As Malaysia is one of the agriculture producers in the world, the demand of an instrument for quality analysis in crops is very high.

Wide ranges of microwave sensors have been used for moisture content (MC) determination in agriculture products. The appropriate sensors are chosen depending on the nature of the dielectric material to be measured, both physically and electrically, the frequency of interest, and the degree of accuracy required. The sensors that have been widely used in agriculture field can be categorized as reflection or transmission types using resonant or non resonant systems, with open or closed structures for sensing of the properties of material samples (Kraszewski, 1980). For the closed structures, it is represented by the waveguide and coaxial line transmission measurements. On the other hands, the open structure can be represented by the free-space transmission measurements and open ended coaxial (OEC) line systems. The resonant structures can be classified as either closed resonant cavities or open resonant structures. These structures can be operated on the types of measurement, where two-port devices suitable for transmission measurements while one port devices are used for the reflection measurements (Nelson, 1998).

There are many factors that can affect the permittivity measurement. Few studies have been carried out for permittivity measurements in the low, medium, and high frequency ranges, including the use of several bridges and resonant circuits (Field, 1954; Corcoran et al., 1970) and concluded that the electrode polarization phenomena at low frequencies can invalidate and affect the measurement data. It also reported by Nelson and Kraszewski (1990a) that the design of the dielectric sample holder for the interest material under test (MUT) is one of the important factor that affect the measurement technique. Previous developed techniques have been developed that applied high frequency for permittivity measurement in grain and seed samples. The Q-meter based on resonant circuit with 1 to 50 MHz range (Nelson, 1991), coaxial sample holders modeled as transmission-line sections with lumped parameters and measured with an RX- meter for the 50 to 250 MHz range (Jorgensenet al., 1970) and for the 200 to 500 MHz range, measured with an admittance meter (Stetson & Nelson 1970) are the examples for the developed techniques. Generally, techniques such as transmission-line, resonant cavity, and free-space techniques have been widely practiced at MW frequencies (1 GHz and above) and have been illustrated in several reviews (Westphal, 1954; Altschuler, 1963; Bussey, 1967).

1.1 Microwave Aquametry

Water is known to be the most important components in agriculture products. Because of this reason, microwave measurement technique is the most appropriate, rapid and precise method in order to perform the quality analysis in crops as water is known to have a strong interaction with the electric field at microwave frequencies. Various techniques have been implemented to determine the MC of agriculture product such as X-rays, magnetic resonance, electrical and magnetic technology, and also near infrared (NIR) spectroscopy (Sunet al., 2010; Ruiz-Altisent et al., 2010; Butzet al., 2003). Among of these techniques, microwave measurement technique is the most practical method for agriculture application based on its unique features (Kraszewski & Nelson, 1995). This technique offers a fast, nondestructive and continuous monitoring of MUT without any alter nor contaminate the material and also low hazard risk towards the operator. The factors such as environmental conditions and negligibility of the effect of DC conductivity are uninfluenced to the measurement and make the moisture measurement easier.

1.1.1 Microwave Sensors

The microwave properties of agriculture products can be rapidly sensed based on the MC measurement by using proper sensors and can well correlate with the product's quality. The permittivity in agriculture products, such as fruits, grains, seeds, plants, vegetables, meats and other foods (Kraszewski & Nelson, 2004) have been measured by using the commercial microwave sensor such as Keysight 85070E Dielectric Probe Kit (Keysight OEC probe). However, the utilization of this sensor with a bulky network analyzer is not cost effective as the network analyzer is quite expensive.

Consequently, there is a high demand for microwave sensors that offers rapid and nondestructive measurement method on the agriculture product which can act as a cost and energy saving real time decision maker for quality determination and preservation during the pre-harvest, harvest and post-harvest process. This is supported by the fact that the low cost and feasible feature of the microwave components has offer a great opportunity for the development of a low-cost microwave instrumentation system which result in significant labor, cost savings that comply with safety regulations. This is relevant with the high consumer's awareness of putting the rules and guidelines regarding the safety standard in the first place.

The general measurement principle for microwave sensors relies on correlating the measured dielectric properties and physical properties of MUT. Dielectric properties are intrinsic electrical properties that characterize the electric field and material interaction. For that reason, development of reliable microwave sensors depends on the accurate determination of the dielectric constant and loss factor, and the robustness of the algorithm correlating these properties with the MC parameter. The microwave sensing technique is highly recommended for water-containing MUT as water dipolar and free water mechanisms are high associated with its dielectric properties at microwave frequencies (Hasted, 1973). For example, the determination of optimal state for preservation process of grain such as harvesting, storage, marketing, and drying utilized MC as the primary parameter (Nelson, 2000).This crucial parameter also has been used in determination of shelf life of food and agriculture products. Previously, the applications of conventional oven-drying and chemical titration methods for MC in-process monitoring are not relevant due to laborious sample preparation.

The choice of the measurement technique is often related to the application type. For wide spread use of these sensors, other factors are to be considered, including cost, portability, and seamless implementation within a given process. Microwave sensors operating at a single frequency are less expensive than those operating at multiple frequencies and easier to calibrate and maintain. Therefore, for a microwave sensor in moisture determination based on the permittivity measurement of the dielectric properties at a single microwave frequency, there is a need to take into account the effects of temperature and bulk density (Trabelsi et al., 1998).

1.1.2 Open Ended Coaxial Sensor

An OEC sensor consists of inner (a) and outer (b) radii of conductor that separated by the lossless homogeneous dielectric material such as Teflon that result in termination of relative permittivity in the plane z=0 into a flat metallic flange in the transverse direction (Pournaropoulos & Misra, 1994). The utilization of OEC line sensor has been widely given attentions as it offers non-destructive feature, easy to use, little sample preparation and also rapid measurement for permittivity and MC of MUTs at wide band of microwave frequencies with a reasonable accuracy ($\pm 5\%$) that only required a small sensing area (Abbas et al., 2005a; Abbas et al., 2005b; Grant et al., 1989; Marsland & Evans, 1987).

The commercialize Keysight OEC probe is made up with rugged structure and materials that allows the measurement to be carried out in a wide -40 to +200℃ temperature range and for corrosive or abrasive materials. The designed flat surface of the sensorsuitable to be used either in liquid or semisolid samples with homogeneous features for broadband permittivity measurements (Grant et al., 1989; Blackham & Pollard, 1997). Besides, this technique has been widely used for permittivity measurements of agriculture products such as fresh fruits and vegetables (Ohlsson et al., 1974; Nelson et al., 1994). The permittivity of the MUTs is calculated by using an equivalent admittance model of the coaxial sensor (Abbas et al., 2005a) based on the reflection coefficient measurement taken when the MUTs are placed against an open end of a coaxial line. The material terminating the aperture is assumed to be homogeneous, isotropic, linear, and nonmagnetic, of complex permittivity extending to infinity. A static capacitance (C), due to the fringing fields excited by the transverse electromagnetic (TEM) fields of the line over the aperture. The measurement configuration of the coaxial line sensor with a ground plane is shown in Figure 1.1.

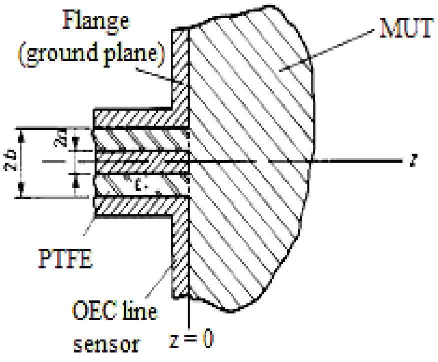

Figure 1.1: The sample measurement setup for OEC line sensor
(Source: Grant et al., 1989)

1.1.3 Complex Permittivity

The complex dielectric permittivity (ε*) is defined based on the interaction between biological materials with electromagnetic fields which divided in two parts: the dielectric constant (ε') and the loss factor (ε"). The equation of complex permittivity based on (Hippel, 1954):

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

The ε' represented by the material's energy storage ability when MUT is exposed to an electric field and have impacts on both the electric field distribution and the phase of waves travelling through the material. The ε" is described as the ability to dissipate energy when MUT is subjected to an applied electric field or various polarization mechanisms that have effects on both energy absorption and attenuation, which results in generation of heat (Ikediala et al., 2000; Mudget, 1986). The amount of thermal energy converted in the food is proportional to the value of the ε" (Sosa-Morales et al., 2010).

The complex permittivity of MUT can also be calculated by using a dielectric mixture model that includes the parameters such as fractional volume and the permittivity of each constituent in the MUT. Both the parameters are essential to be used in calculating the effective permittivity of the mixture. The dielectric mixture equations are suggested previously by (Liu et al., 2009; Jusoh et al., 2011; Subedi & Chatterjee, 1993).

1.2 Problem Statement

In agriculture, MC is among the important factor that closely correlated to the properties of agriculture products. There are a diverse range of techniques (Sun et al., 2010; Ruiz-Altisent et al., 2010; Butz et al., 2003) that have been used for the MC determination in agriculture products but only the microwave moisture technique that has been widely used due to the fast, precise and high sensitivity features of the technique. By using the suitable sensor, the correlation between microwave properties of agriculture products and its quality can be quickly detected. Several sensors such as microstrip and coplanar which based on the attenuation measurement have been suggested previously for the MC determination in oil palm fruits (Khalid & Abbas, 1992; Kent, 1990; Khalid et al., 1996; Khalid & Hua, 1998). However, laborious sensor preparation is required when using these sensors.

The commercial Keysight OEC probe is one of the most widely used microwave OEC sensor for determination of permittivity of moist materials. The Keysight OEC probe has been used to determine the permittivity of oil palm fruits (Yeow, 2003) and ginger (Hassan et al., 2011). However, the Keysight OEC probe requires a network analyzer which is bulky and expensive. As a solution to this limitation, a low cost open ended coaxial-stub contact panel (OEC-SCP) and a monopole sensor have been redesigned which can be used for both the dielectric properties and MC determination in oil palm fruits (Yeow, 2003; Lee, 2004) respectively. However, both these techniques utilized a data acquisition card in conjunction with a PC to retrieve the measured data where the results are computed and displayed on the PC's monitor. In this work and for the first time, a low cost microcontroller-based microwave reflectometer which utilizes the PIC16F690 microcontroller for data acquisition and calibration equation calculation and also directly displays the results on the LCD panel, is developed for the determination of both MC and permittivity of oil palm fruits and ginger using both OEC-SCP and monopole sensors.

The MC in ginger decreases from 91.63% to 78.33% as the rhizome's age increase from 5 to 7 months of planting. Drying is one of the important postharvest processing methods used for ginger preservation. Many of the moisture-mediated deterioration reactions and reproduction of micro-organisms causing decay can be prevented by removal of moisture by appropriate drying method. The small changes in MC as the ginger ages required the usage of a sensor with better performance in reflection measurement. The usage of OEC-SCP sensor is the most suitable as it has a flange that covered large area to maintain a good contact between the surface of the ginger and also the sensor.

For the oil palm fruit, the fruit development highly depends on the changes of MC as the increasing of fruits ages have significantly large differences of MC which from 82% to 30%. As the OEC-SCP sensor has a flange that covered large area, due to the obovoid shape of oil palm fruits, part of the fresh mesocarp is required to be sliced in longitudinal direction so that the good contact between the surface of the mesocarp and the OEC-SCP sensor can be maintained. This will cause the destruction to the oil palm fruits sample. So, a monopole sensor is suggested for the measurement of dielectric properties in oil palm fruits due to the small contact area of the sensor which suitable for the non-destructive features of the MC measurement.

This thesis presents the development of a microcontroller-based microwave reflectometer using both OEC-SCP and monopole sensors for determination of both MC and permittivity of oil palm fruits and ginger. Calibration equations will be established to predict MC and permittivity from the measured reflected voltages from the oil palm fruits and ginger samples. The microwave reflectometer consists of a microwave source, stripline directional coupler, OEC-SCP and monopole sensors, two diode detectors, a microcontroller and a liquid crystal display (LCD) panel. The MC and permittivity results are compared with standard oven drying method and network analyzer, respectively.

1.3 Research Objectives

The main research objectives are:

1. To determine the relationship between the variations in dielectric properties of ginger and oil palm fruit with frequency for different percentage of MC.
2. To examine the effect of MC on the dielectric properties of ginger and oil palm fruit at several selected frequencies.
3. To establish the calibration equation to determine the MC from measured permittivity.
4. To visualize the electric field distribution of the OEC-SCP and monopole sensors due to ginger and oil palm fruit of various percentages of MC.
5. To develop a microwave reflectometer to determine the dielectric properties, MC from the reflected voltage measurement using the OEC-SCP and monopole sensors.

1.4 Thesis Layout

The prime focus in this study is to investigate the implementation of two different types of OEC sensors based on MC determination for the growth development and food preservation applications in oil palm fruit and ginger respectively.

Chapter 2 presents the various application of OEC sensor in agriculture products. This is followed by an overview of techniques for the ripeness determination and postharvest technique that implements in oil palm fruit and ginger respectively.

Chapter 3 describes the theoretical background required for the permittivity calculation based on the measure reflection coefficient of the industrial Keysight OEC probe with MUT. The theory of finite element method (FEM)that applied in COMSOL Multiphysics® software is also covered in this chapter. This chapter also described in details the design and analysis of the stripline directional coupler by using Microwave Office software.

Chapter 4 highlights in details the sample preparation, measurement setup, fabrication of reflectometer, performance testing and software development by using Flowcode. This is follow by computational procedure to visualize the electric field distribution of unloaded and loaded sensor by using COMSOL Multiphysics® software. This chapter also include the experimental procedures to obtain the actual MC, permittivity and reflected voltage of oil palm fruit and ginger based on standard oven drying method and also microwave technique.

Chapter 5 presents the results and discussion. This chapter includes the analysis and discussion in variation of permittivity with frequency at selected MC for both oil palm fruit and ginger. This follows by correlations between the permittivity with MC at selected frequencies is analyzed and discussed. The electric field distribution by using FEM that applied in COMSOL Multiphysics® software for various MC in both MUTs is also visualized and discussed in chapter 5. The calibration equation to predict MC and permittivity based on the measured reflected voltage are presented. The validation of the calibration equations for all the microwave parameters with MC are also presented to determine the equation that will give the highest accuracy in the determination of MC in MUTs.

Lastly, Chapter 6 summarizes all the results and findings obtained in this study. This chapter also presents several recommendations for future works in this study.

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