MICROWAVE REFLECTOMETER FOR SOIL MOISTURE AND PERMITTIVITY MEASUREMENT

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JANUARY 2016

To my beloved family and friends,

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my main supervisor, Dr. You Kok Yeow, who made all this possible, for his help, guidance, patient and support throughout this study. I am grateful to two of my co-supervisors, Assoc. Prof. Dr. Ngasri Dimon and Dr. Tan Tian Swee, who have given advices and suggestions that contributed directly to this thesis.

I appreciate Universiti Teknologi Malaysia for providing me with Zamalah Scholarships for three years and also Ministry of Higher Education Malaysia for providing research grants in order for our research works to proceed. Many thanks to the officers in Radar Communication Laboratory, Faculty of Electrical Engineering, Universiti Teknologi Malaysia.

Finally, special thanks to my family and friends for their continuous encouragement and support throughout the time.

ABSTRACT

Microwave sensors are commonly used for aquametry measurements due to strong tendency of water molecule in absorbing microwave signals. Nowadays, meter-based microwave system is in demand as more applications need concept of being portable and simple. This thesis presents a microwave reflectometer, which operates between 2.2 GHz and 4.4 GHz. It can measure soil moisture content, *m.c.* up to 26 % with mean deviation between predicted and actual *m.c.* determined at ± 2.0 %. Five common soil samples found in southern region of Peninsular Malaysia, Johor were characterized based on macroscopic and microscopic experiments. Throughout the research, four microstrip ring resonantor sensors operating between 2.2 GHz and 4.4 GHz were designed with different angles of microstrip bends. (Conventional Sensor = 0.98 rad., Sensor A = 1.34 rad., Sensor B = 1.57 rad., and Sensor C = 1.64 rad.). Sensor B was chosen as the soil sensor. A critical study on the use of microstrip ring resonator sensors for the determination of both permittivity, ε_r and *m.c.* from the measured scattering parameters (*S*-parameters) in conjunction with E5071C vector network analyzer (VNA) was presented. The relationship between the measured ε_r and *m.c.* obtained from the oven drying method was established. From the results, it was observed that two dielectric relaxation conditions (bound and free water) exist in soil-water mixture. A semi-empirical equivalent lumped element model was created based on simulation data obtained from Microwave Office (AWR) software. The predicted ε_r results from the model agree with the measured data using commercial HP85070D dielectric probe. The model successfully estimated ε_r for the five common soil types with error of 2.5 %. By using inverse algorithm from the model, *m.c.* was predicted and was in good agreement with the standard oven drying method with its average error within ± 1.5 % for all soil samples. In general, microwave reflectometer with the proposed MRR sensor, provide nondestructive measurement for rapid determination of soil *m.c.* and ε_r.

ABSTRAK

Sensor gelombang mikro biasanya digunakan untuk ukuran aquametrik kerana kecenderungan yang kuat pada molekul air dalam serapan isyarat gelombang mikro. Kini, sistem meter gelombang mikro banyak diperlukan kerana kebanyakan aplikasi memerlukan konsep mudah-alih dan kurang komplikasi. Tesis ini membentangkan reflectometer yang beroperasi antara 2.2 GHz dan 4.4 GHz. Reflectometer ini boleh mengukur kelembapan (*m.c.*) tanah sehingga 26 % dengan sisihan minima antara ± 2.0 %. Lima jenis sampel tanah yang biasa ditemui di kawasan selatan Semenanjung Malaysia, Johor telah dicirikan berdasarkan eksperimen makroskopik dan mikroskopik. Sepanjang penyelidikan ini, empat sensor gelombang mikro yang beroperasi antara 2.2 GHz dan 4.4 GHz telah direka dengan pelbagai sudut selekoh mikrostrip. (Sensor Konvensional = 0.98 rad., Sensor A = 1.34 rad., Sensor B = 1.57 rad., dan Sensor C = 1.64 rad.). Sensor B telah dipilih sebagai sensor tanah. Kajian kritikal terhadap penggunaan sensor gelombang mikro untuk menentukan ketelusan (ε_r) and *m.c.* tanah dengan ukuran dalam *S*-parameter melalui penggunaan E5071C penganalisis rangkaian vektor (VNA) telah dibentangkan. Hubungan antara ε_r yang diperolehi dan *m.c.* yang ditentukan dengan kaedah pengeringan oven telah dikenalpastikan. Dua keadaan relaksasi dielektrik (terikat dan bebas) yang berlaku dalam pengukuran tanah telah ditunjukkan daripada analisa keputusan. Model semi-empirik elemen telah dicipta berdasarkan data simulasi yang diperolehi daripada perisian Microwave Office (AWR). Keputusan ε_r yang diramalkan daripada model bersetuju dengan data yang diukur dengan menggunakan HP85070D kit dielektrik. Model ini berjaya menganggarkan ε_r untuk lima jenis sampel tanah dengan ralat 2.5 %. Daripada formula ekoran model ini, penganggaran *m.c.* dapat ditentukan dan bersetuju dengan kaedah pengeringan oven dengan ralat ± 1.5 % untuk semua jenis sampel tanah. Secara umum, reflectometer yang bersepadu dengan sensor yang dicadangkan itu dapat memberikan pengukuran yang tidak memusnahkan sampel dalam penentuan *m.c.* tanah dan ε_r.

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LIST OF ABBREVIATIONS

BW	-	Bound Water
CST	-	Computer Simulation Technology
DAQ	-	Data Acquisition Unit
DC	-	Direct Current
DGS	-	Defected Ground Structure
EDX	-	Energy-Dispersive X-ray
EM	-	Electromagnetic
FDR	-	Frequency Domain Reflectometry
FSS	-	Frequency Selective Surfaces
FW	-	Free Water
GDP	-	Gross Domestic Product
GUI	-	Graphical User Interface
HYMENET	-	Hygrometric Measurement Network
ISM	-	Industrial, Scientific, and Medical
MRR	-	Microstrip Ring Resonator
MSE	-	Mean Squared Error
NI	-	National Instrument
NPK	-	Nitrogen, Phosphorus, and Potassium Analysis
PC	-	Personal Computer
PCB	-	Printed Circuit Board
RF	-	Radio Frequency
RLC	-	Resistor-Inductor-Capacitor
RMSE	-	Root Mean Square Error
SEM	-	Scanning Electron Microscope
SMA	-	SubMiniature version A
SUT	-	Soil Under Test
SWR	-	Standing Wave Ratio

TDR	-	Time Domain Reflectometry
TE	-	Transverse Electric
TM	-	Transverse Magnetic
VCO	-	Voltage Controlled Oscillator
VNA	-	Vector Network Analyzer
VSWR	-	Voltage Standing Wave Ratio

LIST OF SYMBOLS

$m.c.$	-	moisture content
ε_r	-	relative permittivity
ε_r'	-	dielectric constant
ε_r''	-	loss factor
$\lvert\Gamma\rvert$	-	reflection coefficient
$m.c._g$	-	gravimetric moisture content
$m.c._v$	-	volumetric moisture content
$\lvert S_{11}\rvert$	-	return loss
λ	-	wavelength of electromagnetic wave
$\tan\delta$	-	loss tangent
m_{water}	-	weight of water
$m_{drysoil}$	-	weight of dry soil sample
V_{water}	-	volume of water
$V_{drysoil}$	-	volume of dry soil sample
V_{cube}	-	volume of the cavity cube
$\rho_{drysoil}$	-	dry soil bulk density
ρ_{water}	-	density of water
σ	-	conductivity
$\lvert S_{21}\rvert$	-	transmission coefficient
f_r	-	resonant frequency
G_S	-	antenna gain of the sensor
G_M	-	antenna gain of the transmitter and receiver
Q	-	quality factor
P_{RX}	-	power receiver
P_{TX}	-	power transmiter
L_P	-	conversion loss
ε_{eff}	-	effective relative permittivity

r	-	mean radius of the ring
n	-	mode number
c	-	speed of light in vacuum
λ_g	-	guided wavelength
a	-	inside radius of ring
b	-	outside radius of ring
c	-	feed point radius of ring
ψ	-	specific field function
k	-	propagation constant
ω	-	angular frequency
μ_0	-	permeability of free space
ε_0	-	permittivity of free space
J_n	-	*n*th-order Bessel function
Y_n	-	*n*th-order Neumann function
Y_m	-	mutual admittance
E_a	-	radial electric fringing aperture fields at a
E_b	-	radial electric fringing aperture fields at b
Y_s	-	self- admittance
g_s	-	self-conductance
b_s	-	wall susceptances
Z_{in}	-	input impedance
θ_i	-	incident angle
d	-	thickness of grounded plane
w	-	microstrip line’s copper width
h	-	substrate thickness
P_{loss}	-	power loss
L	-	inductance
C	-	capacitance
R	-	resistance
Z_0	-	characteristic impedance of the feed line
θ	-	electrical length
B_{01}	-	susceptance for stubs
θ_s	-	degree of freedom

β_i	-	coupling coefficients
Q_L	-	loaded quality factor
Q_0	-	unloaded quality factor
f_{Unload}	-	unloaded resonant frequency
f_{Loaded}	-	loaded resonant frequency
D	-	filling factor
V_A	-	reflected voltage
V_B	-	incident voltage
$ø$	-	bending angle
Z_{01}	-	impedance of open stub
θ_{01}	-	electrical of open stub
SR	-	size reduction
$S_{\max}$	-	maximum sensitivity
$S_{\min}$	-	minimum sensitivity
S	-	sensitivity
R_s	-	resolution
k_o	-	propagation constant
z	-	distance of transmission line in coaxial cavity
T_{Loaded}	-	transmission coefficient with sample
T_{Unload}	-	transmission coefficient without sample
f_{BW}	-	bandwidth
A	-	calculated deviation length of MRR
G	-	relative average error
f_s	-	frequency shifting

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Microwaves in radio frequency (RF) engineering are a form of electromagnetic radiation with wavelengths ranging from as long as one meter to as short as one millimeter. Microwaves as designated in *S*-band frequency (2 GHz to 4 GHz) are commonly used in human applications, such as microwave oven and communication devices. Since the discovery and development of microwave technologies, these technologies have become common in different fields of study, both commercial and private industries. For this reason, recently, the microwave electronic components are widespread in the market with affordable price. This situation becomes an absolute advantage for researchers to apply microwave technologies to other fields of science, such as food industry, biomedical applications, and agricultural industry. One of the most common microwave products, microwave oven has been introduced in our daily life. The concept of using microwaves in heating the food is due to the polarization of water molecule contained in the sample which is sensitive, and is showing significant response when exposed to microwave energy. Besides, the tendency of water molecule to absorb microwaves, allowing the microwave techniques to be successfully applied in microwave aquametry research with ideas of determining moisture content, *m.c.* in a materials containing water (Troughton, 1969 and Sarabandi and Eric, 1997).

In developing world, agriculture is often seen as a “leading edge” of a region or country’s early commercial growth which has a multiplier effect on the overall economy (Miller, 1995). The concern with soil quality and maintaining it under intensively cropped systems is important. The development of civil engineering due to increase of population in Malaysia has also brought soil quality into significant research study. Soil quality is important in the fact that building cement blocks are made up of soil, water, and cement. Therefore, good monitoring of soil quality will lead to strong building structures. Soil quality is macroscopically and microscopically determined based on physical properties (soil texture, moisture content, *m.c.* and relative permittivity, ε_r) and chemical properties (pH, base saturation, and soil acidity).

Soil moisture content, *m.c.* is categorized as one of the most necessary physical characteristics in various sectors such as agriculture, civil engineering, landscaping, irrigation engineering, and hydrology, since the consistency and workability of a clayey soil strongly depend on its *m.c*. Moisture content, *m.c.* is divided into bound water and free water conditions. You *et al.*, (2013) stated that different soil types may have different bound water and free water levels. There are two standard methods of determining *m.c.* of soil, which are divided into the direct and indirect methods. Direct method determines *m.c.* by removing the water molecules from the soil-water mixture sample with the oven drying technique. This method is accurate but it is not preferable due to time consuming. On the contrary, indirect method requires the measurement of the electrical properties in the soil-water sample by using fabricated instrument, so-called moisture detection meter. The change in electrical properties will be directly correlated with a change in the actual *m.c.* of the respective soil obtained from oven drying method (direct method). Recently, indirect methods become more popular than the direct method due to well continuity of testing, real time measurement, good sensitivity, instantaneous results, and with good user-friendly features (Skierucha and Wilezek, 2010 and You *et al.*, 2013).

The interaction between agri-foods materials with microwave can be described by the complex relative permittivity, ε_r in Equation (1.1).

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

where the real part of permittivity which is known as dielectric constant, ε_r' is an important parameter in food and agricultural industries processing using microwave techniques. On the other hand, the imaginary part, ε_r'' is the dielectric loss factor which is influenced the energy absorption or attenuation of the material. In fact, ε_r'' varies greatly between soil types (Skierucha *et al.*, 2010) due to different trace elements content in soils, terrain either in vegetative or mountainuous structure (Lesmes *et al.*, 1999), and moisture content, *m.c.* (Sarabandi and Eric, 1997, Storme *et al.*, 1999, and You *et al.*, 2013). Both ε_r' and ε_r'' are highly correlated with moisture content, since at microwave frequencies, the electromagnetic energy are mainly absorbed by water and the volume of moisture in the total volume of material most heavily influences the effective relative permittivity of the material. This is due to the relative permittivity of water (ε_r = 80 at DC stage) normally being much greater than that of the other constituents in soil (mineral soil: 4, organic matter: 4, air: 1). If the value of the effective relative permittivity changes in the soil sample, the microwave device will measure a change in reflection /transmission coefficient or resonant frequency that can be directly correlated with a change in moisture content, *m.c.* of the soil, which was obtained from oven drying method. Thus, the dielectric measurements can be used to monitor the moisture content, *m.c.* inside the soil under test. Although measurement of permittivity, ε_r is well established, there is a lack of dielectric characterization study based on different soil types and this further gives great motivation for this overall study. In addition, reliable microwave aquametry measurement system which appears as a useful tool to investigate and determine permittivity, ε_r and moisture content, *m.c.* level of various soil types also not diffusely available worldwide.

There are numerous microwave techniques to determine ε_r', such as microstrip ring resonator (MRR) technique, which has different working principles comparing with the dielectric probe technique, monopole sensing technique, and coaxial cavity technique. Since soil particles are not uniformly distributed, air gap do exists in between soil individual particles. Although dielectric probe technique is fast, but it is less preferred for good measurement technique due to its high sensitivity toward the presence of air gaps and also the applied pressure, which contributes to degradation in term of the accuracy (Sarabandi and Eric, 1997). Generally, monopole structure sensor technique is slightly difficult when burying the sensor into the soil for measurement. Commonly, measurement by using monopole sensor is too sensitive and the obtained results often provide large uncertainties (You *et al.*, 2013). Consequently, decreases the precision and repeatability of the measurement. Coaxial cavity techniques had been widely used to perform nondestructive dielectric constant measurements of materials. This technique is accurate but it is related to difficulties in loading and unloading samples (Joshi *et al.*, 1997). Resonant methods have higher accuracies and sensitivities, and they are most suitable for low-loss samples; in this case; soil samples (Chen *et al.*, 2004).

As a consequence, permittivity, ε_r and moisture content, *m.c.* level of various soil types remain as interesting research topics to be explored by the microwave propagation communities. This research work aimed to fill these knowledge gaps by investigating several physical phenomena and specificities of various soils types particularly in southern region of Peninsular Malaysia, Johor using microwave sensing that could possibly lead to agricultural processing industry using microwave techniques.

1.2 Problem Statement

First problem statement discussed on the necessity for microwave soil aquametry sensor and such measurement is represented in frequency-domain analysis. Time-domain reflectometer, which firstly introduced in 1970's is commonly applied now in most soil measurement study. However, these DC time-domain type sensors can only detect the existence of water and no-water conditions but cannot exactly display a range percentage of moisture content, *m.c.*, which is required at most. Infrared sensor is less precise and sensitive as compared to microwave sensor due to soil sample is in-homogenous and infrared sensing is based on one particular dotted area. Optical technique is also used in soil measurement study. The optical calculation is based on the change of refractive index of sample, *n*. For microwave sensor, it is based on the change of permittivity, ε_r. As know that, $n^2 = \varepsilon_r$. Thus, principally, microwave sensor is more sensitive as compared to optical-type sensor. Moreover, this kind of measurement system cannot provide insight and point out properties that are hard to discern or observe such as the soil permittivity. Representation of soil characteristics is more convenient and intuitive when working in the frequency-domain because signal can be represented by magnitude and phase as functions of frequency.

Malaysia has been a successful developing country, excellent in agriculture and civil construction sectors. Agriculture sector is the main economic supporter in Malaysia. Nearly twenty four percent of Malaysia's land area is composed of land dedicated to agriculture alone. Palm oil is the main commodity in Malaysia's agricultural sector and contributes nearly 9 percent to the Gross Domestic Product (GDP). Malaysia is the second largest producer of palm oil in the world and is responsible for one third of the world's rubber exports. Other agriculture products including rice, cocoa, timber, coconut, and pineapple also contribute to the economics' growth. Soil provides proper nutrition, growth, and life of plants. The optimal soil moisture level is the main factor that affects plants' growth and well development. Recently, civil construction is rapidly developed in Malaysia to provide more homes due to increased of population. Soil is important ingredients in the cement mixture and water defines the soil quality. Consistency in mixing and moisture is the key to good quality concrete block. Maintaining right quantity usage of soil and water in cement block mix not only produces good quality blocks but also cost savings in long term. Therefore, proper control and monitor of soil quality is significant for strong fundamental of buildings. Since water is an important characteristic of many natural and man-made products or is introduced during technological processes, it is quite obvious that measurement and control of moisture content, *m.c.* have great economic contribution and technical importance. Hence, in order to estimate reliable specific moisture content, *m.c.* values of soils for some plantations and constructions, it is therefore of key importance to carefully assess the relationship between soil quality and moisture content, *m.c.* rates from times to times.

Third factor is due to inconsistent soil classifications for every country. The first classification, the International System, was first proposed by Albert Atterberg in 1905, and was based on his studies in southern Sweden for that time agricultural purposes. The soil classification may differ from our country due to different climatic regions. Till today, there is still no uniform data for soil classifications in Malaysia yet. Through the macroscopic and microscopic testing on various soil types in Malaysia, it is possible to find out the interaction between the measurement data and establish the relationship between soil particle sizes and soil dielectric properties. By determining the particle sizes based on soil dielectric properties is considered a novel and non-destructive technique for soil research industry. This is another milestone for us to determine our own particle sizes classifications for Malaysia based on tropical climate. Even though the collected soil database may not applicable for universal use but it is possible to be used as references for current ongoing and future soil research studies.

1.3 Research Objectives

In regards to recent technological advances and problems mentioned above, the main goal of this study is to provide critical information for the moisture variation and permittivity of various soil types, particularly in southern region of Peninsular Malaysia, Johor by developing the reflectometer with resonator type of sensors. More specifically, the main research objectives are listed below:

i. To construct a reflectometer for microwave aquametry measurement at *S*-band and develop a distributed element model to suite the microstrip resonator ring (MRR) sensor for *m.c.* and ε_r measurements of various soil types in Malaysia.

ii. To investigate the relation between *m.c.* and ε_r of various soil types as well as resonant frequency shifting of reflection coefficient, $|\Gamma|$ and propose a soil quality classification using microwave measurement techniques. This database can also be applied for soil in tropical regions around the world.

1.4 Scopes of work

The scope of this research is given as follow:

(1) Review on influence of moisture content, *m.c.* on soil permittivity, ε_r with assumption that higher *m.c.* value will result in higher soil ε_r. Next, investigate frequency-variation method by using microstrip ring resonator (MRR) sensor to differentiate various soil types based on

respective soil dielectric constant, ε_r' and determine moisture content, *m.c.* of respective common soil types. The proposed sensors are designed to operate from 2 GHz to 4 GHz (cover the industrial, scientific and medical (ISM) band) with resonance frequency range between 2.9 GHz and 3.3 GHz.

(2) Design a four-port branch-line directional coupler for the remote sensing *S*-band soil reflectometer. Next, develop the PC controllable configuration for the reflectometer with NI LABVIEW as Graphical User Interface (GUI). MRR sensor is attached together with the meter device for sensing purposes. The calibrated equations are programmed in MATLAB for rapid and real-time determination of soil *m.c.* and soil permittivity, ε_r for various soil types in this study.

(3) Analyze the suitable microstrip ring resonant (MRR) sensor via empirical resistor-inductor-capacitor (*RLC*) distributed element model. The model is developed by applying basic fitting method with simulated values obtained using the microwave office (AWR) simulator from 0.5 GHz to 4.5 GHz over a wide range of relative dielectric constant, ε_r' (1 to 10) and loss tangent, tan δ (0.01 to 0.2). The values for the seven elements (three inductors, two capacitors, and two resistors) are expressed as polynomial functions of ε_r' and tan δ and by using the inverse algorithm with an objective function computed in MATLAB program, the model is sufficient to predict soil permittivity, ε_r and consequently, determining moisture content, *m.c.* of respective soil samples.

(4) Macroscopically testing analysis on respective soil samples for physical properties determination, such as soil's relative permittivity, pH, and moisture content, *m.c.* is performed by using experimental tools, such as HP85070D dielectric probe, HI98127 pH meter, and designed sensors via Keysight 8071C Vector Network Analyzer. On the other hand, microscopic analysis by magnifying the texture of soil

sample using scanning electron microscope (SEM) is carried out to observe the particles' shape and sizes of respective soil samples in different bulk samples. From the captured images, the trace elements contained in respective soil samples can be obtained.

(5) Describe the relationship for relative dielectric properties, ε_r and soil pH based on different moisture content, *m.c.* for various soil types and perform polynomial regression analysis to establish these two relationships.

   i. Develop calibration equations which relate both dielectric properties and various moisture levels by using gravimetric $m.c._g$ and volumetric $m.c._v$ for different soil types for the designed sensors.

   ii. Develop calibration equations which relate which relate both soil pH and moisture content, *m.c.* of various soil types by using gravimetric and volumetric methods for the designed sensors.

(6) Determine bound water and free water conditions based on relationship between measured return loss, $|S_{11}|$ and moisture content, *m.c.* for various soil types. Consequently, develop a concise soil quality classifications based on these dependant factors, together with (4) and (5) for agricultural purposes in Malaysia. Due to time constraint, the measurements will be done on five common soil types (white, yellow, loam, peat, and sand soil) in southern Peninsular Malaysia, Johor. Limitations such as environment and temperature change were excluded because measurements were done inside lab with room temperature (25°C).

1.5 Research Contributions

Different climatic regions and inadequate sensor system result in poor soil study and measurement. In order to establish reliable soil measurement model in tropical climatic regions, accurate significant soil study model with respect to the local climatic study is required. To this aim, this work mainly focused on the characterization of five common soil types specifically devoted to their physical and chemical behavior. The following has been identified to be the main contribution for the requirement of significant soil study model:

i. The main contribution is the development of a frequency domain reflectometer. In electronics, a four-port branch-line directional coupler contains power detectors in both arms of the auxiliary line (Incident and Reflected ports) so as to measure the electrical power flowing in both directions in the main line. From incident and reflected voltages, reflection coefficient, $|\Gamma|$ of the sample under test can be determined. This fabricated microwave reflectometer is a PC controllable measurement system, which attached with suitable microstrip ring resonator (MRR) acting as sensor device that is capable to determine soil gravimetric moisture content, $m.c._g$ up to 26 % $m.c._g$ with mean deviation between actual and predicted within ± 2 % $m.c._g$.

ii. The second contribution is the design and fabrication of microstrip ring resonator (MRR) sensors, operating at *S*-band frequency range. MRR sensor was applied in microwave aquametry measurements due to its highest sensitivity towards the presence of water. The designed MRR sensors were successfully used in this study to characterize various soil types, with average error values of less than 5 %, which are in fine agreement with commercial dielectric probe and cavity perturbation technique. In this study, **Sensor B** chosen as the suitable sensor for soil measurement via proposed microwave reflectometer.

iii. The third contribution is the application of distributed element model for the characterization of the microstrip ring resonator (MRR) sensor in different operating frequencies. This study also utilizes this model according to its microstrip bending angle for every sensor design and determines the suitable operating frequency for suitable agriculture products and also various soil types. By using the inverse algorithm from polynomial functions of ε_r' and tan δ with an objective function computed in MATLAB program, the model is sufficient to predict soil permittivity, ε_r and thus, the prediction of m.c. can be done. The mean deviation between actual and predicted was calculated within ± 1.5 % $m.c._g$. The main advantage of this model lies in its adaptability to the local soil measurement. For this case, the soil samples are commonly found in Malaysia. This model is specifically applicable to soil types in tropical countries. Besides, the flexibility of this model may contribute to more sensor designs for other agriculture products, such as pineapple, palm oil, rice, and cocoa.

iv. The forth contribution is the determination of relationship between soil complex relative permittivity, ε_r and soil moisture content, *m.c.* and also the relationship between soil pH and soil moisture content, *m.c.* The relationships were expressed into polynomial regression equations to determine actual soil moisture content, *m.c.* and soil pH in the absence of the actual moisture and pH measurement.

v. The fifth contribution concerned the soil quality determination. Five common soil samples (white, yellow, peat, loam, and sand) in southern region of Peninsular Malaysia were identified through the soil analysis based on macroscopic and microscopic experimental testing. The physical properties (soil texture, moisture content, *m.c.* and relative permittivity, ε_r) and chemical properties (pH and soil acidity). Statistical significant bound and free water conditions were investigated for each soil type. These parameters are particularly important for proper irrigation process and stored as soil database for future references.

1.6 Thesis Organization

This thesis is presented in six chapters. This chapter introduces the background of the investigated research study, followed by identifying the problem statements and motivations which have led to narrow study into this research. The scientific objectives and significant contributions from this research work are outlined and highlighted with a clear identification of the novel content in the work.

Chapter 2 reviews study on past, recent, and ongoing microwave aquametry research studies with various microwave measurement techniques and applications, followed by the history of evolution and development in agriculture sectors. Some research gaps on the past techniques and sensors are reviewed with relevant data and proofs. It continues with the soil type and quality study based on two main dependant factors, such as moisture content, *m.c.* and pH measurements. Next, study on the reflectometer and architecture of the development, following by the design of microstrip ring resonator (MRR) and also modified design of MRR based on four-legged element structure with different mitered bending angles are reviewed. Besides, study on MRR sensor based on wall admittance calculation and lumped element equivalent circuit formulations are presented. This chapter also presents procedures of modification in lumped element circuit with open stub technique at conventional branch-line directional coupler to achieve smaller branch-line directional coupler and with better performances. Finally, resonant method based on MRR sensor with reflection technique and frequency variation method to determine permittivity and conductivity for respective soil types are presented.

Chapter 3 describes on the research methodology for the design of the proposed MRR sensors and development of microwave soil quality meter for soil quality measurement. It begins with detailed explanation of the research methodology, which consists of five main stages. Section 3.1 describes on MRR sensors' design and simulation, while Section 3.2 presents the fabrication of MRR sensors. Section 3.3 explains on fabrication of the soil meter system, which includes the design of four-port miniaturized branch-line directional coupler. Section 3.4 includes soil under test (SUT) preparation procedures and setup instruments. Last section presents the soil measurement process.

Chapter 4 presents MRR sensor with investigations on admittance model, mitered angle bending's effects on MRR design, power loss and sensitivity, as well as contour mapping of magnetic field. Lumped element modelling consisting of resistor, *R* inductor, *L*, and capacitor, *C* on MRR sensors was presented as follows. The second section discussed on the design of four-port branch-line directional coupler based on performances of coupling, return loss, bandwidth, phase angle between ports as to produce a reliable microwave reflectometer for soil quality determination. Besides, discussions on the assembly of microwave reflectometer and initial results, together with the development of graphical user interface (GUI) for the meter were presented.

Chapter 5 describes the physical and chemical properties of the five common soil samples in Malaysia, namely white, yellow, loam, peat, and sand soil. Besides, the relationships for relative dielectric properties, ε_r and soil pH based on different moisture content, *m.c.* are presented with implementations of polynomial regression equations for the respective soil types by using proposed microwave MRR sensors via vector network analyzer. A lumped element prediction model for suitable microwave MRR sensor based on some key concepts of the distributed elements (resistor, *R*, inductor, *L* and capacitor, *C*) circuits was proposed to estimate the respective soil dielectric constant, ε_r' and consequently, the soil *m.c.* determination. Such predictions are found to be in good agreement with dielectric measurements obtained from a commercial dielectric probe (HP85070D) and actual *m.c.* determination using oven drying technique. This chapter continues with discussions on the results for determining soil ε_r' and *m.c.* by using fabricated microwave soil quality reflectometer. The relationship between shifting frequency, f_s of soil samples and various moisture levels is presented and programmed in MATLAB for results study and analysis. Finally, a soil database based on the above dependant factors for the five common soil types is established and can be used as reference for agriculture sectors and civil engineering in Malaysia.

Chapter 6 discusses the conclusion and future works. The major works in this thesis are concluded and summarized, followed by some constructive recommendations on the further work are given.

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