UNIVERSITI PUTRA MALAYSIA

DETERMINATION OF THE MOISTURE CONTENT IN HEVEA RUBBER LATTEX USING SHORT CIRCUITED WAVEGUIDE TECHNIQUE

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By
PARNIA TOHIDI KALOURAZI

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

May 2014

This thesis is dedicated to
my beloved parents (Pakizeh Ghalandari and Qumars Tohidi)
and
my dear brothers (Pouya and Sahand) who support me with their endless love to carry out my education.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

DETERMINATION OF THE MOISTURE CONTENT IN HEVEA RUBBER LATTEX USING SHORT CIRCUITED WAVEGUIDE TECHNIQUE

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May 2014

Chairperson : Associate Professor Zulkifly Abbas , PhD

Faculty : Science

The thesis describes a short circuited waveguide technique for the determination of moisture content from reflection coefficient measurement of a waveguide loaded with Hevea rubber latex samples. The operating frequencies were from 8 GHz to 12 GHz. The theoretical part includes both the Finite Element Method and Short Circuit Line (SCL) theory to calculate the reflection coefficient of the sample placed in a waveguide. A computer program was written to implement the SCL calculation of the reflection coefficient due to the interaction between the electromagnetic waves and sample in the waveguide. Simulations using Finite Element Method was realized using the COMSOL software. The geometrical problem and the boundary conditions were first defined before performing the simulation of electromagnetic field distribution in the waveguide. The input permittivity of latex require for both SCL and FEM were obtained from measurements using Agilent Dielectric Probe Kit 85070B. Relationships between the dielectric constant, loss factor, moisture content and frequency have been established. The dielectric constant increases linearly with the measured frequency for all percentages of moisture content (*% m.c*). However the loss factor was inversely proportional to the operating frequencies. Samples with higher *% m.c* would give higher values of the dielectric constant and vice versa for the loss factor. The permittivity results were used in the calculation of the reflection coefficient. The FEM results were much closer to the measured values compared to the SCL theory for the whole frequency range between 8 GHz and 12GHz.
Calibration equations to predict the *% m.c* from the measured reflection coefficient have been established. It was found the most accurate equation was based on the measurement

of the magnitude of the reflection coefficient with accuracy within 3 % when compared to the actual mc obtained by the standard oven drying method.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Sarjana Sains

MENENTUKAN KANDUNGAN AIR DALAM SASU GETAH MENGGUNAKAN TEKNIK PANDUGELOMBANG TINTASAN

Oleh

PARNIA TOHIDI KALOURAZI

Bulan dan Tahun Viva Voce diadakan

Mei 2014

Pengerusi : Profesor Madya Dr. Zulkifly Abbas
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Tesis ini memperihalkan teknik pandu gelombang pintasan untuk penentuan kandungan kelengasan melalui pengukuran pekali pantulan pandugelombang yang dibebankan dengan sampel lateks getah Hevea. Frekuensi operasi ialah dari 8 GHz to 12 GHz. Bahagian teori tesis ini merangkumi Kaedah Elemen Terhingga (FEM) dan teori garisan pintasan(SCL) untuk menghitung pekali pantulan sampel yang dimuatkan dalam pandugelombang. Satu program komputer telah dibina menggunakan kaedah SCL.untuk pengiraan pantulan akibat interaksi diantara geleombang elektromagnet dan sampel didala, pandugelombang. Simulasi menggunakan FEM pula dicapai melalui perisian COMSOL. Masalah geometri dan syarat sempadan ditakrifkan terlebih dahulu sebelum memulakan simulasi taburan medan elektromagnet dalam pandugelombang. Nilai ketelusan lateks yang diperlukan sebagai input kepada SCL dan FEM diperolehi melalui pengukuran Pengesan Dielektrik Agilent 85070B. Hubungan persamaan diantara pemalar dielektrik, fakror kehilangan dielektrik, kandungan kelengasan dan frekuensi telah diperolehi. Pemalar dielektrik didapati berubah secara linear dengan frekuensi pengukuran untuk keseluruhan peratusan kelengasan sementara faktor kehilangan dielektrik berubah secara sonsang dengan frekuensi. Sampel dengan kandungan kelengasan yang tinggi memberi nilai pemalar dielektrik yang lebih tinggi dan untuk nilai faktor kehilangan dielektrik, sebaliknya pula berlaku. Nilai ketelusan digunakan dalam pengiraan pekali pantulan. Keputusan pengiraan menggunakan FEM didapati adalah lebih tepat berbanding SCL untuk keseluruhan frekuensi 8 GHz hingga 12 GHz.

Persamaan tentukuran untuk menganggarkan kandungan kelengasan melalui pengukuran pekali pantulan telah dibina. Adalah didapati persamaan paling tepat adalah berdasarkan pengukuran magnitud pekali pantulan dimana ketepatan dalam julat 3% kelengasan boleh dicapai bila dibandingkan dengan kaedah piawaian pengeringan ketuhar.

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Parnia Tohidi
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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:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Symbol	Quantity	Units
E	Electric Field Intensity	(V/m)
H	Magnetic Field Intensity	(A/m)
S	Pointing Vector	(W/m^2)
ε_0	Permittivity of Vacuum	(F/m)
ε^*_r	Relative Permittivity (Complex)	dimensionless)
μ^*_r	Relative Permeability (Complex)	dimensionless)
ε'	Real part of Relative Permittivity/Magnetic Constant	(F/m)
ε''	Imaginary of Relative Permittivity/Loss Factor	(F/m)
μ'	Real part of Relative Permeability/Magnetic Constant	(H/m)
μ''	Imaginary of Relative Permeability/Loss Factor	(H/m)
Z	Impedance	(Ω)
α	Attenuation Constant	(1/m)
γ	Propagation Constant (complex)	(1/m)
β	Phase Constant	(rad/m)
σ	Conductivity	(S/m)
F	Frequency	(Hz)
ω	Angular Frequency	(rad.Hz)
Tanδ	Loss Tangent	(dimensionless)
S_{11} ,S_{21}	Scattering Parameters	(dimensionless)
S_{12} ,S_{22}	Scattering Parameters	(dimensionless)
J	The Current Density	(A/m)
K	Wave Number	(rad/m)
d	Sample Thickness	(m)

CHAPTER 1

INTRODUCTION

The rubber industry is a major source of income in Malaysia. Since World War II, rubber has contributed very much to Malaysian economy, as a result of which Malaysia is still one of the largest rubber-growing countries in the world. The Malaysian rubber industry has evolved over years into an integrated entity where rapid changes in the medium and downstream have turned it to a multi-billion Ringgit industry. Considerable progress in the design and manufacturing of rubber based products led to the increasing demand in both local and global markets. The statistics of rubber production, exports and domestic consumptions in Malaysia during the mid-2013 are shown in Figure 1.1. More than 60,000 tons of rubber were exported whilst only 35,000 tons were for domestic consumption.

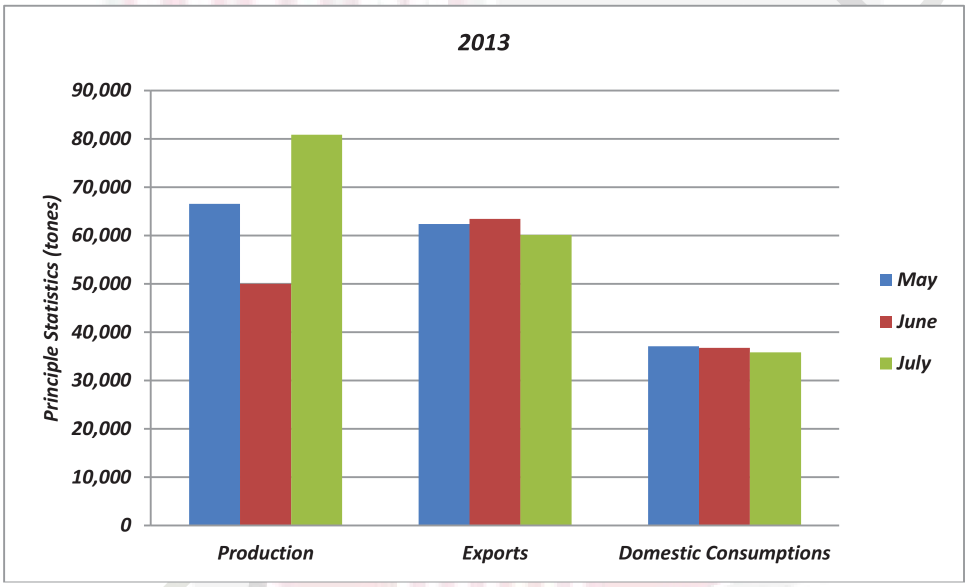


Figure 1.1.Monthly rubber statistics, Malaysia 2013 (Source:(Department of Statistic Malaysia, Official Portal, 2013))

1.1 An Overview of Hevea Rubber Latex

Rubber tree originated from Central and South America. Natural rubber, the main solid component of Hevea latex, is obtained by tapping the rubber trees. Latex composition varies according to type of clone, tree age, seasonal changes, the utilization, soil conditions, contamination, tapping system, etc. (Khalid and Mohamad Daud, 1992)

Latex tapped from a rubber tree is essentially a white discharge from the subcutaneous tissue of the tree. According to Poh (Poh, 1989) and Tomazic-Jezic (Tomazic-Jezic et al., 2004) the main components of natural latex are rubber particles (30 - 40%), water (40 - 65%), protein (2 - 3%), sterilglycosides (0.1 - 0.5%), resin (1.5- 3.5%), ash (0.5 -1.0%), and carbohydrate (1.0 - 2.0%). Rubber particles and water are more than other components in Natural latex. Chin (Chin, 1979) considered latex as a complex mixture consisting of 55-80% water, 15-40% of rubber hydrocarbon, and 3-5% of non-rubber solid. The basic components of the non-rubber solid (NRS) are proteins, lipids, quebrachitol, and inorganic salts. The NRS also has a small portion of organic salt, approximately 0.5%, which includes phosphate ions (~0.25%), potassium (~0.12-0.25%), and a bit of copper, iron, calcium, sodium, and magnesium (Cook and Sekhar, 1953). The total concentration of organic salts is approximately 0.5% which consists of phosphate ions (~0.25%), potassium (0.12-0.25%), and small amounts of copper, iron, calcium, sodium, and magnesium (Cook and Sekhar, 1953).

In the rubber industry, latex rubber prices depend on the percentage of dry rubber content (DRC) or total solids content (TSC) or moisture content (*m.c.*). In general, the dry rubber content (DRC) of fresh latex is normally between 20 to 40 percent and less than TSC. Rubber smallholders supply almost half of the whole world production of latex, which is sold to a collector, paying according to DRC, TSC, or *m.c.* Approximately half of the total world production of latex comes from rubber smallholdings. Latex collected by smallholders is sold to a collector who pays according to the DRC or TSC or *m.c.* Finding a suitable technique for accurate determination of the true DRC or *m.c.* is considered really important to policy makers. It is important that the true *DRC* or *m.c.* of latex is determined correctly to ensure a fair price is paid to the tapper. There are various techniques to determine the content of latex, each of which is discussed in chapter 2. The various techniques proposed to determine latex concentration will be discussed in Chapter 2.

1.2 Microwave Sensors

Microwaves are electromagnetic waves with frequencies between 300 MHz (0.3 GHz) and 300 GHz (Pozar, 2005; Sorrentino and Bianchi, 2010). The prefix "micro-" in "microwave" originated from the historical terminology, then microwaves have smaller wavelength than radio broadcasting signals which were called short wavelength usually denoted by SW. The boundaries between far infrared light, terahertz radiation, microwaves, and ultra-high-frequency radio waves are fairly arbitrary and are used variously between different fields of study. Microwaves are used in spacecraft communication, and much of the world's data, TV, and telephone communications are transmitted through long distances between ground stations and communications satellites by microwaves. Microwaves are also employed in microwave ovens and in radar technology.

Microwave technology has been used extensively for point-to-point telecommunication (i.e., non broadcast uses). The waves can be easily focused into narrower beams than radio waves, allowing frequency reuse. Antenna sizes are smaller if working at higher frequencies because antenna size is inversely proportional to transmitted frequency. Its comparatively higher frequencies allow broad bandwidth and high data transmission rates. Microwave sensors were introduced in the 1960s but were not given much attention by science and industry due to its various limitations. The microwave sources were bulky, expensive, unreliable and lacked safety measures. Also the lack of understanding of the effect of material properties such as moisture content, density or temperature on the permittivity was a disadvantage for the microwave techniques to gain support from the industry. However with advent of telecommunication industry and advanced computational electromagnetic software, the interest in new applications began to grow as the devices are now more compact, cheaper, more reliable and available in shielded packages.

In recent years, there has been an increasing interest to apply microwaves to detect moisture content (*m.c*) in agricultural products. The amount of *m.c.* in a fruit is very important as it affects the quality, stability and development of the fruit. The storability of fruits and vegetables are also influenced by *m.c.* Excessive long-term storage of the product degrades fruits and vegetables quality, resulting in direct economic loss (Ali et al., 2011).

Microwave sensors can be found in almost all major industries including health, environment and agriculture. The principles and limitations of microwave sensors must be known before applying them to any industrial problem. The most popular type of microwave sensors are the commonly used microwave components or transmission lines as shown in Figure 1.2 :

1. Details of the various types of sensors are discussed in Chapter 2. In this work, the Hevea latex sample shall be placed in a waveguide terminated with a metal wall. All the waveguide walls are conductors. Some parts of wave incident on the interface between air and sample in the waveguide are transmitted and some are reflected. The transmitted wave propagates in the sample and is reflected when reaches the metal wall at the other end face of the sample.

2. The various elements to be considered when deploying microwave sensors are frequency range, bandwidth, power handling capability, attenuation, size and fabrication technique.

Some of the advantages of microwave sensors include (Nyfors and Vainikainen, 1989):

i. Non mechanical contact with the object which is especially important in continuous process.

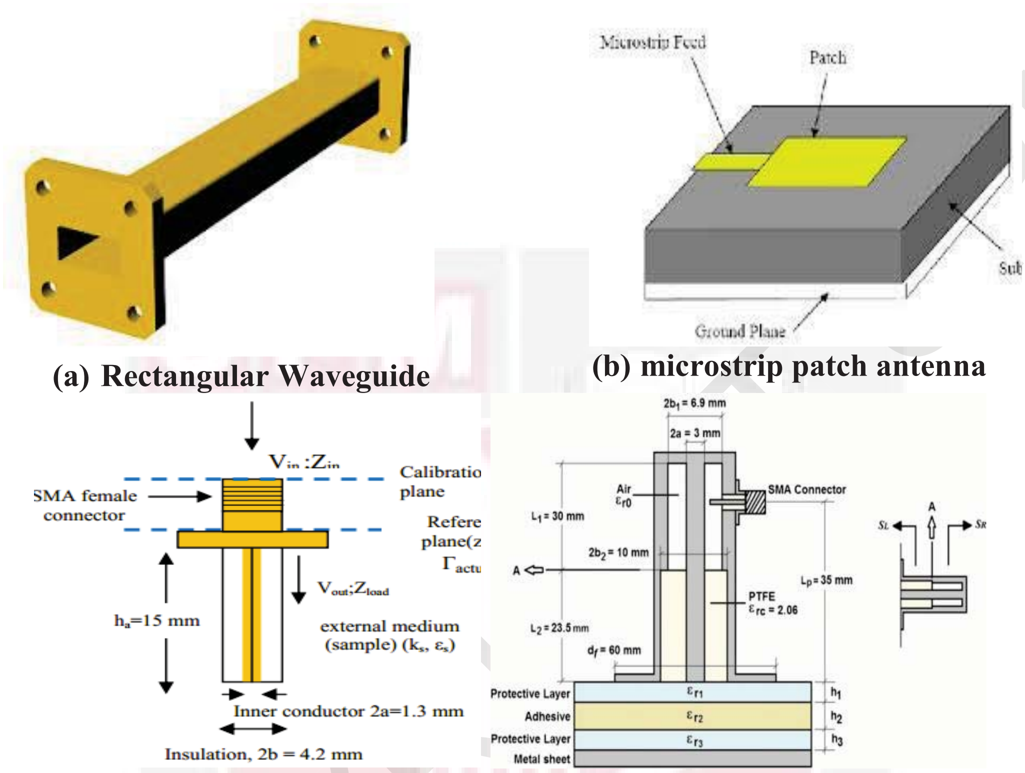
ii. Insusceptible to environmental conditions, such as water vapour and dust (contrary to infrared method) and high temperatures (contrary to semiconductor sensors);

iii. Negligible effect of dc conductivity. Capacitive and resistive measurements at low frequencies are affected by DC Conduction, which is extremely dependant on the temperature and ion content of the material under test. The later highly affects the material conductivity. However, the effect of dc conductivity almost disappeared at microwave frequencies.

iv. Safe electromagnetic wave probing. Microwaves are non-ionizing radiation. Additionally, the output power for most microwave sensors is very much below the safety standard (Ahlbom et al., 1998).

v. Fast and non-destructive technique

Because of its importance in modern life, especially in agriculture, a large number of existing and potential applications of microwave techniques have been reported by many researchers (Khalid et al., 1988).



(a) Rectangular Waveguide **(b) microstrip patch antenna** **(c) monopole** **(d) open-ended coaxial line**

Figure 1.2.Some Examples of Microwave Sensors. (Source: (Ansarudin et al., 2012; García-Baños et al., 2012))

The *m.c.* in various types of liquid or solid materials discussed in this section are for different microwave techniques. Determination of moisture content was used microwave techniques that it is known as a microwave aquametry. Microwave aquametry is generally recognized based on the fact of both dielectric constant (ε') and loss factor (ε'') otherwise they are based on water above the dry ingredients in a microwave. During recent years, many microwave techniques in many applications have been introduced to the wet ingredients *m.c.*

Basically, microwave techniques include simultaneous measurement of amplitude and phase of the electromagnetic wave through a layer of a test substance. Parameters are related to water content and dry weight and moisture content of the material under test. It was subsequently developed into a device that measured both phase (ϕ) and was calibrated with simultaneous linear equations dependent on both of the material variables. Materials can be placed in a waveguide, resonator or in a free space, and the microwave frequency of operation should be adapted for the structure and properties of the material. Measurement and calculation of reflection and transmission coefficients of plane electromagnetic waves from a dielectric layer is essential (Chope, 1960; Klein, 1981; Kupfer, 2000; Stuchly and Kraszewski, 1965). Great demand for the electromagnetic properties of the dielectric material is determination of the reflection coefficient.

Dielectric aquametry is based on the systematic variation of the dielectric properties of the material or the system considered with its water content (Brandelik and Huebner, 2000). Therefore, the necessity for optimizing the dielectric aquametry is to study and understand dependence on the dielectric properties of water content for different classes of materials at the molecular level. In general, by using microwave techniques the dielectric properties of the material can be obtained. Generally, this technique is applied for measuring permittivity and electrical properties of liquid and solid samples including density, moisture content, maturity of the crops, and so on.

1.3 Dielectric Properties of Materials

The parameters involved in the electromagnetic waves interaction with materials are absorption, scattering, attenuation, reflection and transmission. Various fast and accurate microwave methods have been proposed for rapid determination of food quality and agricultural products. The dielectric properties of the material are usually represented by its complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$). The real part of the permittivityε' called dielectric constant describes the ability of the material to store energy, whilst the imaginary part (ε'') refers to the dielectric loss factor which is a measure of the dissipation by the material under applied electromagnetic field.

The permittivity of material depends on a variety of physical phenomenon. The main contributions to the permittivity of a dielectric material are ionic conduction, dipolar characterization and electronic polarization. For moist materials such as Hevea rubber latex, bothε' andε'' are much dependable on the amount of *m.c.* in the sample which influences the degree of polarization. The relationship between ε' and ε'' is basically based on behaviour of the polar molecules is governed by the Debye Relation (Ramo et al., 1994) . The electronic and atomic polarizations develop instantly in the presence of electric fields but the polar molecules turn slowly and exponentially approaching the final state of polarization with a time constant τ called *relaxation time*. In the absence of the electric field, the process goes in reverse order.

When the field is switched off, the sequence is reversed and disorder is restored with the same time constant. At low frequencies, the effect of ionic conductivity is the main contribution factor to the values of ε''. However, the ionic conductivity is very small at microwave frequencies (Nyfors and Vainikainen, 1989).

1.4 Problem Statements

Moisture content in freshly tapped natural rubber latex is between 40 and 65%. Bad practices such as diluting the latex with water could result in a conflict between buyer and seller. Various techniques have been developed to determine the quality of Hevea latex. The quality of latex can be assessed either by the determination of total solid content, dry rubber content or moisture can be grouped into microwave and other non microwave techniques. The microwave techniques include open ended coaxial (Jumiah et al., 1997), monopole (Ansarudin et al., 2012) ,microstrip (Yahaya et al.) and horn waveguide techniques (Khalid, 1982) . The monopole sensors were found to be most accurate when compared to the actual moisture content. Unfortunately, the accuracy of the monopole sensor depends on the length of the monopole and the volume size of the sample. In contrast, the non microwave techniques such as the hydrometer technique (Fleenor and Stott, 1980), titration (Schwarzenbach and Flaschka, 1969), buoyancy (Turner, 1979) and optical (Yariv, 1976) were either inaccurate, time consuming, laborious or required skillful worker to operate the apparatus.

An alternative solution is to use the short circuit line or usually called the short circuited waveguide (SCW) technique. The technique was first introduced by Von Hippel (Von Hippel, 1953) to measure permittivity of solid samples. However the technique is getting less popular due to new advances in microwave technology where the combined transmission reflection technique (TR) is now the more preferred choice for permittivity measurement of solid samples having low loss, low dielectric constant values. However, it should be noted that the sample thickness must be sufficiently thick for TR method to calculate the reflection coefficient. For liquids or semi liquids, this will result in a no uniform density distribution of the sample especially if the measurements were to be implemented with the waveguides in the vertical position. In contrast, the SCW technique does not require the sample to be infinitely thick. However several issues need to be resolved for the SCW technique to be a suitable candidate for accurate measurement of moisture content in latex. These issues formed the main research objectives added in section 1.5. Thus the interaction between the electromagnetic magnetic waves and the Hevea latex samples of varying percentages of moisture content must be investigated.

1.5 Research Objectives

This thesis presents a detailed investigation on the theoretical and experimental analyses of the microwave properties of a thin layer of latex placed in a short circuited waveguide in the frequency range between 8 GHz and 12 GHz. The frequency range was chosen to ensure negligible effect of AC conductivity on the values of the reflection coefficient. The main research objectives include:

i. To design the computational geometrical problem and simulate the field distribution in the waveguide due to the interaction between the electromagnetic waves and sample in the waveguide using Finite Element Method and to develop a computer program in MATLAB to calculate the reflection coefficient of the sample loaded

ii. To measure the permittivity of Hevea rubber latex of various percentages of *m.c.*; also to compare measured and calculated values of both the magnitude and phase of the reflection coefficient using transmission line theory and finite element method;

iii. To determine the relationship between *mc*, magnitude and phase of the reflection coefficient of the sample loaded waveguide and to determine the effect of *mc* in Hevea latex on the variation in both the magnitude and phase of the reflection coefficient.

iv. To determine the accuracy of the short circuit in the prediction of *mc* in the sample.

1.6 Scope of the Study

The focus on this study is limited to the interaction between electromagnetic waves with Hevea rubber latex in a waveguide backed with a metal plate in the frequency range from 8 GHz to 12 GHz. Chapter 2 reviews the various techniques in the determination of DRC and *m.c.* for Hevea rubber. Chapter 3 presents the theory of short-circuited waveguide. Both the transmission line theory and finite element methods were discussed in detail. The methodology and experimental set-up used in this work are presented in Chapter 4. The chapter also includes a detail description of FEM procedure to calculate the reflection coefficient using the COMSOL software. The calculated and measured reflection coefficients are compared in Chapter 5. The chapter also provides an analysis on the various calibration equations for prediction of *m.c.* based on the measured reflection coefficient. Comparison between predicted *m.c.* and actual *m.c.* for all the equations are also presented. Chapter 6 is the conclusion of the thesis summarizing the main contributions and recommendations for future works.

REFERENCES

Ahlbom, A., Bergqvist, U., Bernhardt, J., et al. (1998). Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). International Commission on Non-Ionizing Radiation Protection. *Health Phys, 74*(4), 494-522.

Alex, R., Premalatha, C. K., Nair, R. B., and B, K. (2003). Measurement of dry rubber content of fresh natural rubber latex by a titration method. *Journal of Rubber Research, 6*(4), 221-230.

Ali, A. H., Abbas, Z., Hassan, J. B., Jusoh, A., and Zahari, R. (2011). Microwave antenna sensing technique for determination of moisture content in Hevea Latex from Hevea Brasiliensis tree. *Australian Journal of Crop Science, 5*(11), 1326-1333.

Ansarudin, F., Abbas, Z., Hassan, J., Yahaya, N. Z., and Ismail, M. A. (2012). A Simple Insulated Monopole Sensor Technique for Determination of Moisture Content in Hevea Rubber Latex *measurment science review 12*, 6.

Baker-Jarvis, J., Janezic, M., Grosvenor, J., and Geyer, R. (1992). Transmission/reflection and short-circuit line methods for permittivity measurements. *Nati. Inst. Stand. Technol., NIST Tech. Note, 1355*.

Blackham, D. V., and Pollard, R. D. (1997). An improved technique for permittivity measurements using a coaxial probe. *Instrumentation and Measurement, IEEE Transactions on, 46*(5), 1093-1099.

Booton, R. (1992). Computational methods for electromagnetics and microwaves, John Wiley and Sons, New York.

Brandelik, A., and Huebner, C. (2000). Subsurface sensing, subsurface aquametry. *Subsurface Sensing Technologies and Applications, 1*, 365-376.

Brenner, S. C., and Scott, L. R. (2008). *The mathematical theory of finite element methods* (Vol. 15): Springer.

Brunfeldt, D. R. (1987). *Theory and Design of a Field-Portable Dielectric Measurement System.* Paper presented at the IGARSS Symposium, Ann Arbor, Michigan.

Chen, L. F., Ong, C. K., Neo, C. P., Varadan, V. V., and Varadan, V. K. (2004). *Microwave Electronics: Measurement and Materials Characterization*: John Wiley & Sons, England.

Chin, H. C. (1979). RRIM Training Manual on Analytical Chemistry (pp. 67): Research Institute Malaysia, Kuala Lumpur

Chope, R. H. (1960). US Patent 3, 898.

Collin, R. E. (1991). *Field Theory of Guided Waves*: IEEE Press : New York (2nd ed.).

Cook, A. S., and Sekhar, B. C. (1953). Fraction brown Hevea brasilinsis latex centrifuged at 59,000g. *Journal of Rubber Institute Malaya, 14*, 463.

http://www.statistics.gov.my/portal/index.php?option=com_content&view=article&id=902. (2013). Department of Statistic Malaysia, Official Portal.

Fleenor, W., and Stott, G. (1980). Hydrometer test for estimation of immunoglobulin concentration in bovine colostrum. *Journal of Dairy Science, 63*(6), 973-977.

García-Baños, B., Catalá-Civera, J. M., Peñaranda-Foix, F. L., Canós, A. J., and Sahuquillo-Navarro, O. (2012). Microwave sensor system for continuous monitoring of adhesive curing processes. *Measurement Science and Technology, 23*(3), 035101.

George, N. A., Peethan, A., and Vijayan, M. (2013). A simple optical sensor for the measurement of dry rubber content in natural rubber latex. *Nondestructive Testing and Evaluation, 28*(4), 313-320.
Guo, L. F., Zhao, Z. M., and Gao, M. J. (2005). Study of the compatibility between light-cured repair materials and composite materials by holographic interferometry. . *Optical Engineering, 44*(10), 1056021-1056023.
Gutierrez, E., Loupy, A., Bram, G., and Ruiz-hitzky, E., , . (1989). Inorganic solids in "dry media" an efficient way for developing microwave irradiation activated organic reactions. *Tetrahedron Letter, 30*(8), 945-948.
Hasted, J., and Roderick, G. (1958). Dielectric properties of aqueous and alcoholic electrolytic solutions. *The Journal of Chemical Physics, 29*, 17.
Hasted, J. B. (1973). *Aqueous Dielectric*: London: Chapman and Hall.
Jayanthy, T., and Sankaranarayanan, P. E. (2005). Measurement of Dry Rubber Content in Latex Using Microwave Technique. *Measurement Science Review, 5*(3), 50-54.
Jebbor, N., and Bri, S. (2012). A microwave method for complex permittivity extraction of thin materials. *Journal of Microwaves, Optoelectronics and Electromagnetic Applications, 11*(2), 285-295.
Jiao, D., and Jin, J.-M. (1999). Fast frequency-sweep analysis of microstrip antennas on dispersive substrate. *Electronics Letters, 35*(14), 1122-1123.
Jin, J.-M., and Jin, J. (2002). *The finite element method in electromagnetics*: Wiley New York.
Jin, J.-M., and Riley, D. J. (2009). *Finite element analysis of antennas and arrays*: Wiley. com.
Jin, J.-M., and Volakis, J. L. (1991). Electromagnetic scattering by and transmission through a three-dimensional slot in a thick conducting plane. *Antennas and Propagation, IEEE Transactions on, 39*(4), 543-550.
Julrat, S., Chongcheawchamnan, M., Khaorapapong, T., et al. (2012). Single-Frequency-Based Dry Rubber Content Determination Technique for In-Field Measurement Application. *Sensors Journal, IEEE, 12*(10), 3019-3030.
Jumiah, H., Kaida, K., and W. Mohammad Daud, W. Y. (1997). Microwave Dielectric Properties of Hevea Rubber Latex in the Temperature Range of -30°C to 50°C. *Pertanika Journal Science & Technology. , 5*(2), 179-190.
Kaatze, U., Pottel, R., and Wallusch, A. (1995). A new automated waveguide system for the precise measurement of complex permittivity of low-to-high-loss liquids at microwave frequencies. *Measurement Science and Technology, 6*(8), 1201.
Kent, G. (1988a). Dielectric resonances for measuring dielectric properties. *Microwave Journal, 31*(10), 99-114.
Khalid, K. (1982). Determination of dry rubber content of hevea latex by microwave technique. *Pertanika, 5*(2), 192-195.
Khalid, K., Ghretli, M. M., Abbas, Z., and Ionel, V. G. (2006). *Development of Planar Microwave Moisture Sensors for Hevea Rubber Latex and Oil Palm Fruits.* Paper presented at the 2006 International RF and Microwave Conference Putrajaya, Malaysia : 12 - 14 September, 2006.
Khalid, K., and Mohamad Daud, W. (1992). Dielectric properties of natural rubber latex at frequencies from 200 MHz to 2500 MHz. *Journal of natural rubber research, 7*.
Khalid, K., Zaidan, A. W., and Kasmani, A. R. (1988). Microwave Drying of Hevea Rubber Latex and Total Solid Content (TSC) Determination. *Pertanika Journal Science & Technology., 11*(2), 289-297.

Klein, A. (1981). Comparison of Attenuation and Phase Measurement. *Joumal of Microwave Power, 16*, 289-304.
Knöchel, R., Daschner, F., and Taute, W. (2001). Resonant microwave sensors for instantaneous determination of moisture in foodstuffs. *Journal of Food Control, 12*(7), 447–458.
Kraszewski, A., and Kulinski, S. (1976). An Improved Microwave Method of Moisture Content Measurement and Control. *Industrial Electronics and Control Instrumentation, IEEE Transactions on, IECI-23*(4), 364-370.
Kuang, W., and Nelson, S. O. (1997). Dielectric relaxation characteristics of fresh fruits and vegetables from 3 to 20 GHz. *Journal of Microwave Power and Electromagnetic Energy, 32*(2), 114-122.
Kumar, J., Hussain, R. R., and Philip, S. N. (2007). Measurement of dry rubber content of natural rubber latex with a capacitive transducer. *Journal of Rubber Research, 10*(1), 17-25.
Kupfer, K. (2000). Microwave Moisture Measurement Systems and their Applications *Sensors Update Vol. 7, RF&Microwave Sensing of Moist Materials, Food and other Dielectric*: Wiley-VCH Verlag Weinheim / New York.
Li, J. (2006). Analysis of systematic errors in ISO 126-1995 for the determination of dry rubber content. *Modern Science Instrumentation 6*, 84-85.
Liu, S., Wu, J., Zhang, L., and Dong, H. (2011). Wide-band Rock and Ore Samples Complex Permittivity Measurement.
Lucas, E. W., and Fontana, T. P. (1995). A 3-D hybrid finite element/boundary element method for the unified radiation and scattering analysis of general infinite periodic arrays. *Antennas and Propagation, IEEE Transactions on, 43*(2), 145-153.
Malaysian Standard. (1987). MS 466: Methods of Sampling and Testing Field Latex (First Revision): SIRIM : Standard & Research Institute of Malaysia.
Marincic, A., Benson, F. A., and Tealby, J. M. (1986). Measurements of permittivity by the use of surface wave in open and closed structure. *IEE Microwaves, Antennas and Propagation Proceedings-H, 133*(6), 441-449.
Mei, K. (1974). Unimoment method of solving antenna and scattering problems. *Antennas and Propagation, IEEE Transactions on, 22*(6), 760-766.
Metaxas, A. a., and Meredith, R. J. (1983). Industrial microwave heating.
Meyer, W., and Schilz, W. (1982). Microwave measurement of moisture content in process material *Philips Technology Review, 40*, 112-119.
Nelson, S. O., and Samir, T. (2010). Measurement of Grain and Seed Microwave Permittivity for Moisture and Density Determination.
Nicolson, A., and Ross, G. (1970). Measurement of the intrinsic properties of materials by time-domain techniques. *Instrumentation and Measurement, IEEE Transactions on, 19*(4), 377-382.
Nyfors, E., and Vainikainen, P. (1989). *Industial Microwave Sensors*: Norwood MA, Artech House, Inc.
Nyshadham, A., Sibbald, C. L., and Stuchly, S. S. (1992). Permittivity measurements using open-ended sensors and reference liquid calibration-an uncertainty analysis. *Microwave Theory and Techniques, IEEE Transactions on, 40*(2), 305-314.
Poh, K. W. (1989). Developments of natural rubber latex. Production, properties, stability. *Elastomerics, 12* (12), 12-15.
Pozar, D. M. (2005). *Microwave Engineering* (3rd ed.): John Wiley & Sons, Inc. : New Jersey, USA.

Ramo, S., Whinnery, J. R., and Van Duzer, T. (1994). *Fields and Waves Communication Electronics* (3rd Edition ed.): John Wiley & Sons, Inc., New York.
Sadiku, M. N., and Peterson, A. F. (1990). *A comparison of numerical methods for computing electromagnetic fields.* Paper presented at the Southeastcon'90. Proceedings., IEEE.
Samir, T., Nelson, S. O., and Ramahi, O. (2006). *A Low-Cost Microwave Moisture Sensor.* Paper presented at the Proceedings of the 36th European Microwave Conference, Manchester UK.
Schulz, J., Frank, C., and Hill, C. (1984).
Schwarzenbach, G., and Flaschka, H. (1969). Complexometric titrations.
Shanmuganantham, T., Raghavan, S., and Sriram Kumar, D. (2007). *Comparison of numerical techniques for rectangular microstrip patch antenna.* Paper presented at the Applied Electromagnetics Conference, 2007. AEMC 2007. IEEE.
Silvester, J., and Kleinrock, L. (1983). On the capacity of multihop slotted ALOHA networks with regular structure. *Communications, IEEE Transactions on, 31*(8), 974-982.
Silvester, P. P., and Ferrari, R. L. (1996). *Finite elements for electrical engineers*: Cambridge university press.
Snyder, A. W., and Love, J. (1983). *Optical waveguide theory* (Vol. 190): Springer.
Sorrentino, R., and Bianchi, G. (2010). *Microwave and RF engineering* (Vol. 1): John Wiley & Sons.
Stuchly, S., and Kraszewski, A. (1965). Method for the determination of water content in solids, liquids and gases by means of microwaves and arrangement for application of this method. *Polish Patent, 51*, 731.
Thakur, K. P. (1999). *Modelling the dielectric constant of rice grains.* Paper presented at the Proceedings of 3rd workdshop on electromagnetic wave interaction with water and moist substances, Athens, Argentina
Tillekerathe, L. M. K., Karunanayake, L., Sarath Kurnara, P. H., and Weeraman, S. (1989). A Rapid and Accurate Method for Determining the Dry Rubber Content and Total Solid Content of NR Latex. *Polymer Testing, 8*, 353-358.
Tøgersen, G., Arnesen, J. F., Nilsen, B. N., and Hildrum, K. I. (2003). On-line prediction of chemical composition of semi-frozen ground beef by non-invasive NIR spectroscopy. *Meat Sci., 63*(4), 515-523.
Tomazic-Jezic, V. J., Beezhold, D. H., Hashim, H., et al. (2004). Performance of methods for the measurement of natural rubber latex (NRL) proteins, antigens and allergens. *Journal of Allergy and Clinical Immunology, 113*(78).
Turner, J. S. (1979). *Buoyancy effects in fluids*: Cambridge University Press.
Van, B. (1967). Dielectric behaviour of heterogeneous systems. *In: Progress in Dielectrics, 7*, 69-114.
Von Hippel, A. R. (1953). *Dielectric Materials and Application*: Cambridge, MA:MIT Press.
Wen-Chuan Guo, Nelson, S. O., Samir, T., and Stanley, J. K. (2007). 10-1800 MHz dielectric properties of fresh apples during storage. *Journal of Food Engineering, 83*, 562-569.
Yahaya, N., Abbas, Z., Ismail, M., and Ali, B. M. Determination of Moisture Content of Hevea Rubber Latex Using a Microstrip Patch Antenna.
Yariv, A. (1976). Introduction to optical electronics.
Zhang, J., Chen, X. D., Piao, R. G., and Li, S. Y. (2008). Near infrared spectrometer with

double detectors for food component analysis. *Optics Precision, 16*(6), 986-992.
Zhao, Z. M., Jin, X.-d., Zhang, L., and Yu, X.-l. (2010). Novel measurement system for dry rubber content in concentrated natural latex based on annular photoelectric sensor. *International Journal of Physical Sciences, 5*(3), 251-260.
Zhao, Z. M., Xin, Y. J., Wang, L. X., et al. (2008). Measurement and analysis of absorption spectrum of human blood. *Spectroscopy Spectral Analysis 28*(1), 138-140.
Zhu, W. H., Zhao, Z. M., Guo, X., and Chen, H. (2009). Study of cholesterol concentration based on serum UV2Visible absorption spectrum. *Spectroscopy Spectral Analysis, 9*(4), 1004-1007.