UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF CONDUCTOR-BACKED COPLANAR WAVEGUIDE (CBCWG) MOISTIJRE SENSORS

TEOH LAY HUA

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DEVELOPMENT OF CONDUCTOR-BACKED COPLANAR WAVEGUIDE (CBCWG) MOISTURE SENSORS

by

TEOH LAY HUA

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Specially dedicated to:

Mom, Dad, Brother, Sister
and
Lee Wai Mun

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LIST OF ABBREVIATIONS

CBCWG	conductor-backed coplanar waveguide
ε_r	relative permittivity
ε_{r1}	relative permittivity of substrate
ε_{r2}	relative permittivity of covered cbcwg
ε_{r3}	relative permittivity of test sample
ε_{r4}	relative permittivity of protective layer
ε^*	complex permittivity
μ^*	complex permeability
ε'	dielectric constant
ε''	dielectric loss
ε_r^*	relative complex permittivity
ε_m^*	relative complex permittivity of mixture
ε_w^*	relative complex permittivity of water
ε_l^*	relative complex permittivity of oil
ε_f^*	relative complex permittivity of fibre
V_w	volume fractions of water
V_l	volume fractions of oil
V_f	volume fractions of fiber
M_r	realtive moisture content
M.C.	moisture content
W_T	total mass of mixture
W_w	mass of water in mixture
W_l	mass of oil in mixture
W_f	mass of fiber in mixture
ρ_T	total density of mixture
ρ_w	density of water in mixture
ρ_l	density of oil in mixture
ρ_f	density of fiber in mixture
h	height of substrate (h_1)
s	height of covered layer ($h_2 - h_1$)
d	height of test sample ($h_3 - h_2$)
f	height of protective layer ($h_4 - h_3$)
K_h	$\cosh k_i h$
K_s	$\cosh k_i s$
K_d	$\cosh k_i d$
K_f	$\cosh k_i f$
S_h	$\sinh k_i h$

S_s	sinh $k_i s$
S_d	sinh $k_i d$
S_f	sinh $k_i f$
T_f	tanh $k_i f$
C_h	coth $k_i h$
C_s	coth $k_i s$
C_d	coth $k_i d$
C_f	coth $k_i f$
v_p	phase velocity
Z_o	characteristic impedance
C	capacitance per unit length
C_a	capacitance per unit length of air
ε_{eff}	effective dielectric constant
q_1	filling factor of layer 1
q_2	filling factor of layer 2
q_3	filling factor of layer 3
α	attenuation constant
β	phase constant
γ	propagation constant
σ	conductivity
ω	angular frequency
E(0)	complex amplitude of wave at a reference plane
E(d)	complex amplitude of wave at distance d
S_{11}, S_{12} S_{21}, S_{22} S'_{11}, S'_{12} S'_{21}, S'_{22} S''_{11}, S''_{12} S''_{21}, S''_{22}	scattering parameters
l_1	length of 2-layer cbcwg
l_2	length of sensing area
Γ	reflection coefficient
APB	ratio of inner strip (A) to B (A+gap)
SPH	ratio of thickness of protective layer (S) over height of substrate (H)
BMAPH	ratio of gap (B-A) over height of substrate (H)

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

DEVELOPMENT OF THE CONDUCTOR-BACKED COPLANAR WAVEGUIDE (CBCWG) MOISTURE SENSOR

By

TEOH LAY HUA

October 1997

Chairman : Associate Professor Kaida Khalid, Ph.D.

Faculty : Science and Environmental Studies

Conductor-backed coplanar waveguide (CBCWG)[1] moisture sensor has been developed for a quick and accurate determination of moisture content in fresh mesocarp of the oil palm fruits and cocoa beans. The sensor consists of three parts i.e., the coupling system representing the transition between coaxial line to the CBCWG, the 2-layer structure of the CBCWG and sensing area. Previous work done shows a close relationship between the oil content and moisture content in the oil palm mesocarp during fruit development. The quality of cocoa beans were also affected by the moisture content in the beans. Thus, by measuring the moisture content in the oil palm mesocarp and cocoa beans, the quality of the oil palm fruit and the cocoa beans can be obtained indirectly.

[1] CBCWG is also written as CBCPW

A functional relationship has been developed between scattering parameter S_{21} of the sensor and moisture content of the sample. The reflection and transmission phenomena in the sensor structure can be represented by a signal flow graph and can be simplified by using Mason's non-touching loop rules. The calculation of S_{21} is based on the quasi-transverse electromagnetic mode approximation. Based on the theoretical analysis, computer programmes written in FORTRAN programming language were developed to do the calculations of the attenuation. A total of four different sensors were developed in order to find out the effect of different gap between the conducting strip and upper ground plane and protective layers on the attenuation values.

It is found that the big gap sensor gives a better sensitivity as compared to the small gap sensor. This effect is probably due to the field density in the big gap sensor is much higher than the small gap sensor. The sensitivity of the sensor is also drastically affected by the thickness of the protective layer. This is due to the decreasing of the interaction between the field and the sample as the thickness of the protective layer increases. A comparison between the theoretical and experimental results for the oil palm mesocarp was done. A close agreement has been found. The difference in value ranges from only 1-4dB.

The fine relationship between the attenuation and moisture content for this kind of sensor gives the possibility for the development of a compact and portable microwave instrument for assessing the quality of cocoa and oil palm fruits that are sent to the factory.

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

PEMBINAAN SENSOR PEMANDU GELOMBANG SESATAH TERSOKONG KONDUKTOR (PGSTK) UNTUK PENENTUAN KELENGASAN (AIR)

Oleh

TEOH LAY HUA

Oktober 1997

Pengerusi : Profesor Madya Kaida Khalid, Ph.D.

Fakulti : Sains dan Pengajian Alam Sekitar

Sensor pemandu gelombang sesatah tersokong konduktor (PGSTK) telah dibina untuk penentuan kandungan air dalam buah kelapa sawit dan koko secara cepat dan tepat. Sensor tersebut terdiri daripada tiga bahagian, iaitu sistem penyambungan yang mewakili peralihan talian sepaksi kepada PGSTK, struktur 2-lapisan PGSTK dan tapak pengukuran. Satu perhubungan rapat telah didapati di antara kandungan minyak dan kandungan air di dalam buah kelapa sawit semasa buah matang. Kualiti buah koko juga dipengaruhi oleh kandungan air di dalam buah. Maka, dengan mengukur kandungan air di dalam buah, kualiti buah kelapa sawit dan koko boleh didapati secara tidak langsung.

Satu perkaitan telah dibina di antara parameter penyerakan sensor, S_{21} dan kandungan air di dalam sampel. Fenomena pantulan dan penghantaran gelombang mikro di dalam struktur sensor boleh diwakili oleh graf aliran isyarat dan boleh dipermudahkan dengan menggunakan peraturan lingkaran-tak-bersentuh Mason. Pengiraan S_{21} adalah berdasarkan mod penghampiran kuasi elektromagnet melintang. Berdasarkan analisis teori, program komputer dalam bahasa pengaturcaraan FORTRAN telah ditulis untuk mengira pengecilan gelombang mikro. Empat sensor telah direka untuk mengetahui kesan jurang di antara strip konduktor dengan satah bumi atas dan kesan lapisan perlindungan yang berbeza terhadap pengecilan gelombang mikro dan sensitiviti sensor.

Didapati sensor dengan jurang besar adalah lebih sensitif jika dibandingkan dengan sensor dengan jurang kecil. Ini kemungkinan besar disebabkan oleh ketumpatan medan sensor jurang besar adalah lebih tinggi daripada sensor jurang kecil. Kepekaan sensor juga dipengaruhi dengan ketara oleh ketebalan lapisan perlindungan. Ini disebabkan oleh pengurangan interaksi di antara medan dengan sampel apabila lapisan perlindungan bertambah tebal. Keputusan teori dan eksperimen untuk buah kelapa sawit telah dibandingkan. Satu perkaitan yang rapat telah didapati dan perbezaan nilai teori dan eksperimen hanyalah di antara 1-4dB.

Perkaitan yang baik di antara pengecilan gelombang mikro dan kandungan kelengasan (air) untuk sensor jenis ini membolehkan pembinaan sebuah alat mikrogelombang yang kecil dan mudah alih untuk penilaian kualiti buah koko dan kelapa sawit yang dihantar ke kilang.

CHAPTER 1

INTRODUCTION

This project involves the development of conductor-backed coplanar waveguide (CBCWG) moisture sensors for various agricultural products such as oil palm fruits and cocoa. Khalid and Abbas (1992) developed a microstrip sensor for determination of harvesting time for oil palm fruits. A functional relationship has been developed between insertion loss, $/S_{21}/$, of the sensor and moisture content in mesocarp. It was also shown that a close relationship exists between oil content and moisture content during fruit development. Thus, the oil content and subsequently the time to harvest the fruit bunch can be determined from moisture content.

The sensors were also used to measure the moisture content in cocoa beans. Ripe cocoa, which has a moisture content of approximately 70 %, was fermented for a week to develop the chocolate flavours and aroma. After fermentation, the cocoa has a moisture content of about 56 %. The cocoa was then left to dry out in the sun. The attenuation measurements were then taken everyday using the CBCWG sensors to determine the moisture content of the cocoa. The moisture content calculated from the attenuation was then compared to the moisture content obtained using the standard oven-dry method.

In this chapter, a brief discussion on the conductor-backed coplanar waveguide is given. Though the microstrip line has been widely used as a transmission line, it was later observed that the sensitivity of the coplanar waveguide was substantially better due to the high field concentration between the conducting strip and ground plane. Another ground plane may be placed on the other side of the substrate for easier heat removal. This modified structure is the conductor-backed coplanar waveguide (CBCWG). A review on the oil palm fruit and cocoa is also given. As the quality of the cocoa products is influenced by the fermentation and drying process, a summary of the fermentation and drying process is described. The objective and also a chapter organisation of the thesis is also given.

Conductor-Backed Coplanar Waveguide

The microstrip line has been widely used as a transmission line (Gupta et al., 1979) as well as a component in microwave integrated circuits (Gupta and Singh, 1974). A problem encountered when attempting to measure high moisture content materials using microwave attenuation technique is that, to maintain the attenuation within reasonable limits, say less than 50 dB, very thin or small quantities of sample must be used to keep the propagation path length in the sample small. This is either inconvenient or impossible. It has been pointed out (Kent, 1972) that microwave stripline offers distinct advantages in this respect since only a small part of the sample interacts with the stripline whilst there is no restriction on the size of the sample.

In this case, the line was supported on a substrate material of relatively low dielectric constant (<10) and covered fully or in part by a 'wet' substance of relatively high permittivity (>15). The fringing field interacts with the substance and produces a change in the attenuation constant of the line. The change in the attenuation constant can be calibrated in terms of moisture content or other parameters which affect the dielectric properties of the material. Later, it was observed (Rowe et al., 1983) that the sensitivity of the coplanar waveguide was substantially better than that of microstrip, on account of the high field concentration between the conducting strip and ground. Coplanar waveguide (Fig. 1.1) was invented by Wen (1969) as a

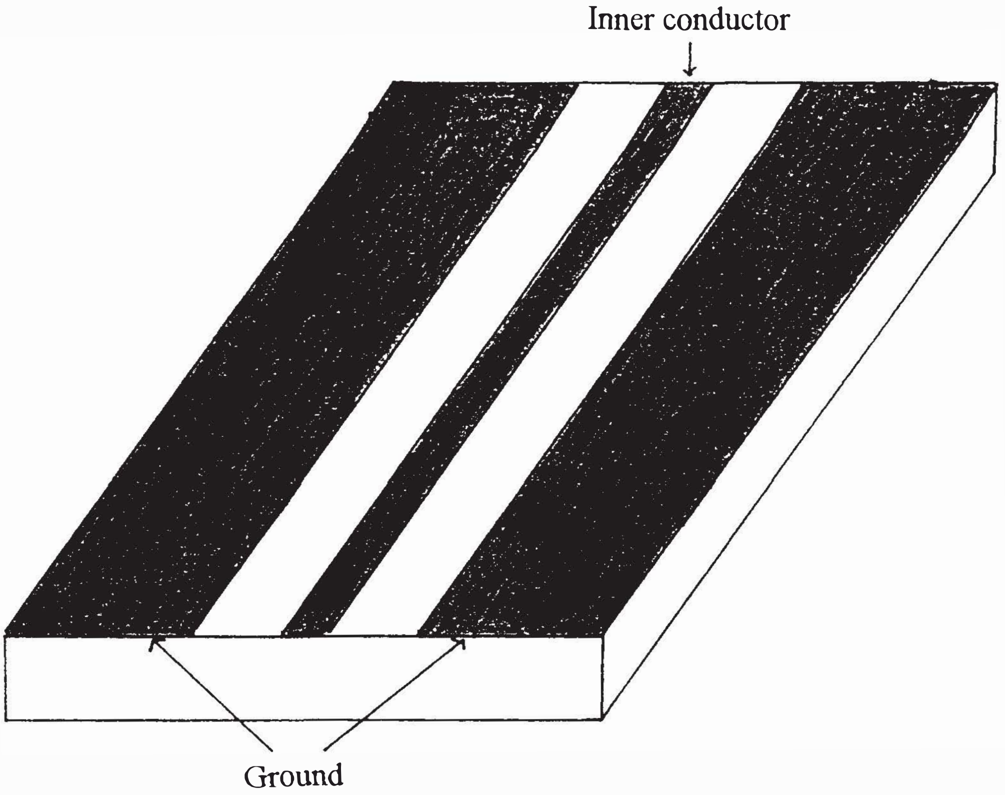

Fig.1.1 Coplanar Waveguide.

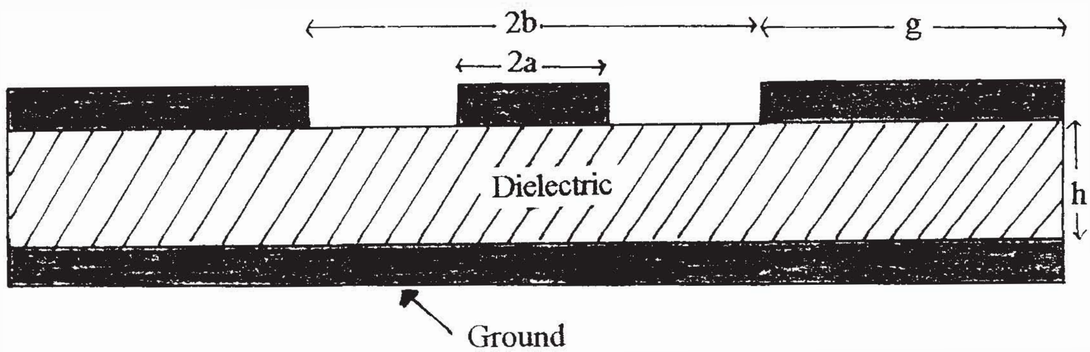

Fig. 1.2 Conductor-backed Coplanar Waveguide.

planar transmission line which is made of a center strip on the surface of a substrate with two ground planes placed adjacent and parallel to the strip. All three conductors in the coplanar waveguide are on the same side of the substrate. Since the dominant mode is quasi-transverse electromagnetic (quasi-TEM), there is also no low frequency cutoff. This mode is a balanced mode.

However, heat removal from an active device is not easy. An additional ground plane may be placed on the other side of the substrate as shown in Fig. 1.2. This modified structure is called the conductor-backed coplanar waveguide. The presence of the ground plane increases the capacitance of the coplanar waveguide and thereby alters its impedance. Fig. 1.3 shows the field concentration of the stripline and Fig. 1.4 shows the field concentration of the conductor-backed coplanar waveguide. Therefore, in this project conductor-backed coplanar waveguide sensor is used.

The analysis of the sensor starts with a 4-layer conductor-backed coplanar waveguide. (Refer to Fig. 1.5). From the diagram, 2a is the width of the conducting strip and 2b is the width of the conducting strip plus the width of the gap. Thus, the gap of the sensor is (b-a). The length of the upper ground is given the symbol g. ε_{r1}, ε_{r2}, ε_{r3} and ε_{r4} are respectively the relative permittivity of the substrate, the protective layer, the test sample and the protective layer. Similiarly, h, s, d and f are the height of the substrate, protective layer, test sample and protective layer respectively.

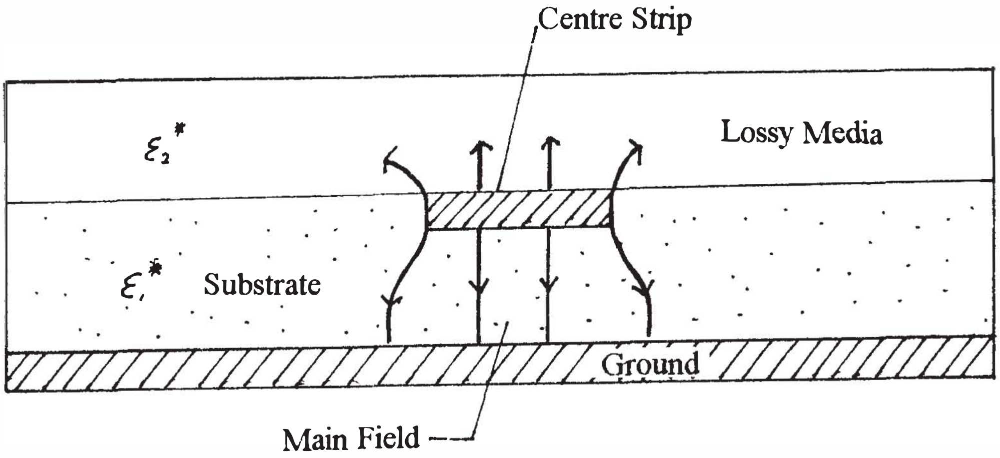

Fig. 1.3 Field Concentration of Microstrip

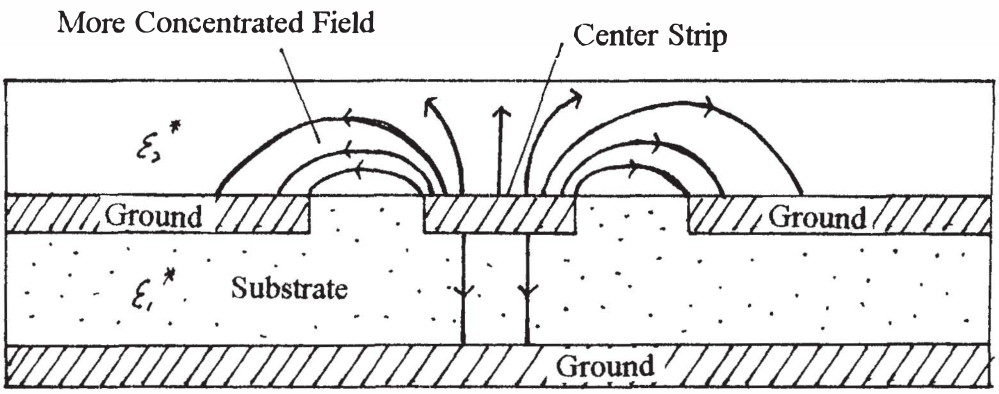

Fig. 1.4 Field Concentration of Conductor-backed Coplanar Waveguide.