



UNIVERSITI PUTRA MALAYSIA

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

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

by

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**Thesis Submitted in Fulfillment of the Requirements for the
Degree of Master of Science in the Faculty of
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Specially dedicated to:

*Mom, Dad, Brother, Sister
and
Lee Wai Mun*



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TABLE OF CONTENTS

		Page
ACKNOWLEDGEMENTS.....		iii
LIST OF TABLES.....		vi
LIST OF FIGURES.....		xiii
LIST OF PLATES.....		xiii
LIST OF ABBREVIATIONS.....		xiv
ABSTRACT.....		xvi
ABSTRAK.....		xiii
CHAPTER		
1	INTRODUCTION.....	1
	Conductor-backed Coplanar Waveguide.....	2
	A Review on Oil Palm Fruit.....	7
	A Review on Cocoa.....	9
	Fermentation.....	10
	Drying.....	12
	Objectives.....	13
	Chapter Organization.....	13
2	MICROWAVE AQUAMETRY.....	15
	Definition of Microwaves.....	15
	Microwave Aquametry.....	16
	Advantages of Microwaves Moisture Measurements.....	17
	Measurement of Moisture Content.....	18
	Application of Coplanar Line as a Moisture Sensor.....	20
	Properties of Materials.....	20
	Variation in Dielectric Properties with Moisture Content and Mixture Model.....	22
	Summary.....	25



3	THEORETICAL ANALYSIS	26
	The Analysis of Multi-layer Structure.....	26
	TEM Analysis of a 4-layer CBCWG.....	27
	Characteristic Impedance of CBCWG.....	41
	Dielectric Loss.....	42
	Calculation of the Total Attenuation of the Sensor.....	47
	Development of Computer Programmes for Determination of Attenuation of CBCWG at Various Moisture Contents.....	52
	Summary.....	56
4	METHODOLOGY.....	57
	Sensor Design.....	57
	Measurement Procedures.....	71
	Summary.....	77
5	RESULTS AND DISCUSSION.....	78
	Experimental Results.....	78
	Comparison Between the Theoretical and Experimental Results.....	83
	Summary.....	101
6	CONCLUSION.....	103
	Conclusion.....	103
	Recommendations for Future Work.....	106
	REFERENCES.....	108
	APPENDICES.....	111
	A Mason's Non-touching Loop Rule.....	112
	B Computer Programmes.....	115
	C Tables of Results.....	130
	VITA.....	150



LIST OF TABLES

Table		Page
3.1	Abbreviations used in the Computer Programmes.....	55
4.1	Dimensions of the Sensors.....	64
4.2	Characteristic Impedance Values with Different Values of BMAPH for Substrate with $\epsilon_r = 2.2$ (Type 2).....	130
4.3	Characteristic Impedance Values with Different Values of BMAPH for Substrate with $\epsilon_r = 2.2$ (Type 3).....	131
4.4	Characteristic Impedance Values with Different Values of BMAPH for Substrate with $\epsilon_r = 10.5$ (Type 2).....	132
4.5	Characteristic Impedance Values with Different Values of BMAPH for Substrate with $\epsilon_r = 10.5$ (Type 3).....	133
4.6	Dielectric Loss Values with Different Values of SPH for 2.2 SGAP (Theoretical).....	134
4.7	Dielectric Loss Values with Different Values of SPH for 2.2 BGAP (Theoretical).....	135
4.8	Dielectric Loss Values with Different Values of SPH for 10.5 SGAP (Theoretical).....	136
4.9	Dielectric Loss Values with Different Values of SPH for 10.5 BGAP (Theoretical).....	137
4.10	Attenuation Values with Different Values of SPH for 2.2 SGAP (Theoretical).....	138
4.11	Attenuation Values with Different Values of SPH for 2.2 BGAP (Theoretical).....	139
4.12	Attenuation Values with Different Values of SPH for 10.5 SGAP (Theoretical).....	140
4.13	Attenuation Values with Different Values of SPH for 10.5 BGAP (Theoretical).....	141



5.1	Attenuation Values with Different Values of SPH for 2.2 SGAP (Oil Palm Mesocarp).....	142
5.2	Attenuation Values with Different Values of SPH for 2.2 BGAP (Oil Palm Mesocarp).....	143
5.3	Attenuation Values with Different Values of SPH for 10.5 SGAP (Oil Palm Mesocarp).....	144
5.4	Attenuation Values with Different Values of SPH for 10.5 BGAP (Oil Palm Mesocarp).....	145
5.5	Attenuation Values with Different Values of SPH for 2.2 SGAP (Cocoa).....	146
5.6	Attenuation Values with Different Values of SPH for 2.2 BGAP (Cocoa).....	147
5.7	Attenuation Values with Different Values of SPH for 10.5 SGAP (Cocoa).....	148
5.8	Attenuation Values with Different Values of SPH for 10.5 BGAP (Cocoa).....	149



LIST OF FIGURES

Figure	Page
1.1 Coplanar Waveguide.....	3
1.2 Conductor-backed Coplanar Waveguide.....	3
1.3 Field Concentration of Microstrip.....	5
1.4 Field Concentration of Conductor-backed Coplanar Waveguide.....	5
1.5 Structure of a 4-layer Conductor-backed Coplanar Waveguide.....	6
1.6 The Oil Palm Tree and Bunch.....	8
1.7 The Anatomy of Cocoa Beans.....	10
3.1 Structure of the Sensor.....	28
3.2a 4-layer Conductor-backed Coplanar Waveguide.....	36
3.2b Semi-infinite 4-layer Conductor-backed Coplanar Waveguide.....	36
3.3a 3-layer Conductor-backed Coplanar Waveguide.....	37
3.3b Semi-infinite 3-layer Conductor-backed Coplanar Waveguide.....	37
3.4a 2-layer Conductor-backed Coplanar Waveguide.....	38
3.4b Semi-infinite 2-layer Conductor-backed Coplanar Waveguide.....	38
3.5a Equivalent 4-layer Conductor-backed Coplanar Waveguide.....	43
3.5b Equivalent 3-layer Conductor-backed Coplanar Waveguide.....	43
3.5c Equivalent 2-layer Conductor-backed Coplanar Waveguide.....	44
3.6a Conductor-backed Coplanar Waveguide Sensor with Sample Inserted.....	48
3.6b Equivalent 2-port Network.....	49



3.7	Simplified Signal Flow Graph using Mason's Non-touching Loop Rule.....	50
3.8	Block Diagram of the Computer Programmes used for Determination of Attenuation of CBCWG Moisture Sensors.....	53
4.1	Characteristic Impedance vs APB for Different BMAPH for 2-layer CBCWG with $\epsilon_r = 2.2$	59
4.2	Characteristic Impedance vs APB for Different BMAPH for Semi-infinite 3-layer CBCWG with $\epsilon_r = 2.2$	60
4.3	Characteristic Impedance vs APB for Different BMAPH for 2-layer CBCWG with $\epsilon_r = 10.5$	62
4.4	Characteristic Impedance vs APB for Different BMAPH for Semi-infinite 3-layer CBCWG with $\epsilon_r = 10.5$	63
4.5	Diagram on the Construction of the Sensor.....	65
4.6	Dielectric Loss vs Moisture Content for Different SPH for 2.2 SGAP.....	67
4.7	Dielectric Loss vs Moisture Content for Different SPH for 2.2 BGAP.....	68
4.8	Dielectric Loss vs Moisture Content for Different SPH for 10.5 SGAP.....	69
4.9	Dielectric Loss vs Moisture Content for Different SPH for 10.5 SBAP.....	70
4.10	Attenuation vs Moisture Content for Different SPH for 2.2 SGAP (Theoretical).....	72
4.11	Attenuation vs Moisture Content for Different SPH for 2.2 BGAP (Theoretical).....	73
4.12	Attenuation vs Moisture Content for Different SPH for 10.5 SGAP (Theoretical).....	74
4.13	Attenuation vs Moisture Content for Different SPH for 10.5 BGAP (Theoretical).....	75



4.14	Attenuation as a Function of Frequency for (a) Sensor in air (b) Fruit with 22.8% Moisture Content (c) Fruit with 78.2% Moisture Content.....	76
5.1	Attenuation vs Moisture Content for Different SPH for 2.2 SGAP (Oil Palm Mesocarp).....	79
5.2	Attenuation vs Moisture Content for Different SPH for 2.2 BGAP (Oil Palm Mesocarp).....	80
5.3	Attenuation vs Moisture Content for Different SPH for 10.5 SGAP (Oil Palm Mesocarp).....	81
5.4	Attenuation vs Moisture Content for Different SPH for 10.5 BGAP (Oil Palm Mesocarp).....	82
5.5	Attenuation vs Moisture Content for Different SPH for 2.2 SGAP (Cocoa).....	84
5.6	Attenuation vs Moisture Content for Different SPH for 2.2 BGAP (Cocoa).....	85
5.7	Attenuation vs Moisture Content for Different SPH for 10.5 SGAP (Cocoa).....	86
5.8	Attenuation vs Moisture Content for Different SPH for 10.5 BGAP (Cocoa).....	87
5.9	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0 (2.2 SGAP).....	89
5.10	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.04 (2.2 SGAP).....	89
5.11	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.08 (2.2 SGAP).....	90
5.12	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.13 (2.2 SGAP).....	90
5.13	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.18 (2.2 SGAP).....	91
5.14	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.22 (2.2 SGAP).....	91



5.15	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.08 (2.2 BGAP).....	92
5.16	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.13 (2.2 BGAP).....	92
5.17	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.18 (2.2 BGAP).....	93
5.18	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.22 (2.2 BGAP).....	93
5.19	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.26 (2.2 BGAP).....	94
5.20	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0 (10.5 SGAP).....	95
5.21	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.06 (10.5 SGAP).....	95
5.22	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.11 (10.5 SGAP).....	96
5.23	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.17 (10.5 SGAP).....	96
5.24	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.22 (10.5 SGAP).....	97
5.25	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.28 (10.5 SGAP).....	97
5.26	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0 (10.5 BGAP).....	98
5.27	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.06 (10.5 BGAP).....	98
5.28	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.11 (10.5 BGAP).....	99
5.29	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.17 (10.5 BGAP).....	99



5.30	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.22 (10.5 BGAP).....	100
5.31	Comparison Between Theoretical and Experimental Results for Oil Palm Mesocarp for SPH=0.28 (10.5 BGAP).....	100



LIST OF PLATES

Plate		Page
4.1	The Four Sensors Designed.....	66
4.2	The Setup of the Equipment.....	66



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_i^*	relative complex permittivity of oil
ϵ_f^*	relative complex permittivity of fibre
V_w	volume fractions of water
V_i	volume fractions of oil
V_f	volume fractions of fiber
M_r	relative moisture content
M.C.	moisture content
W_T	total mass of mixture
W_w	mass of water in mixture
W_i	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_i	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}	
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

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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

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Oktober 1997

Pengerusi : Profesor Madya Kaida Khalid, Ph.D.

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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 pengecalan 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 pengecalan 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 pengecalan 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 klang.

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

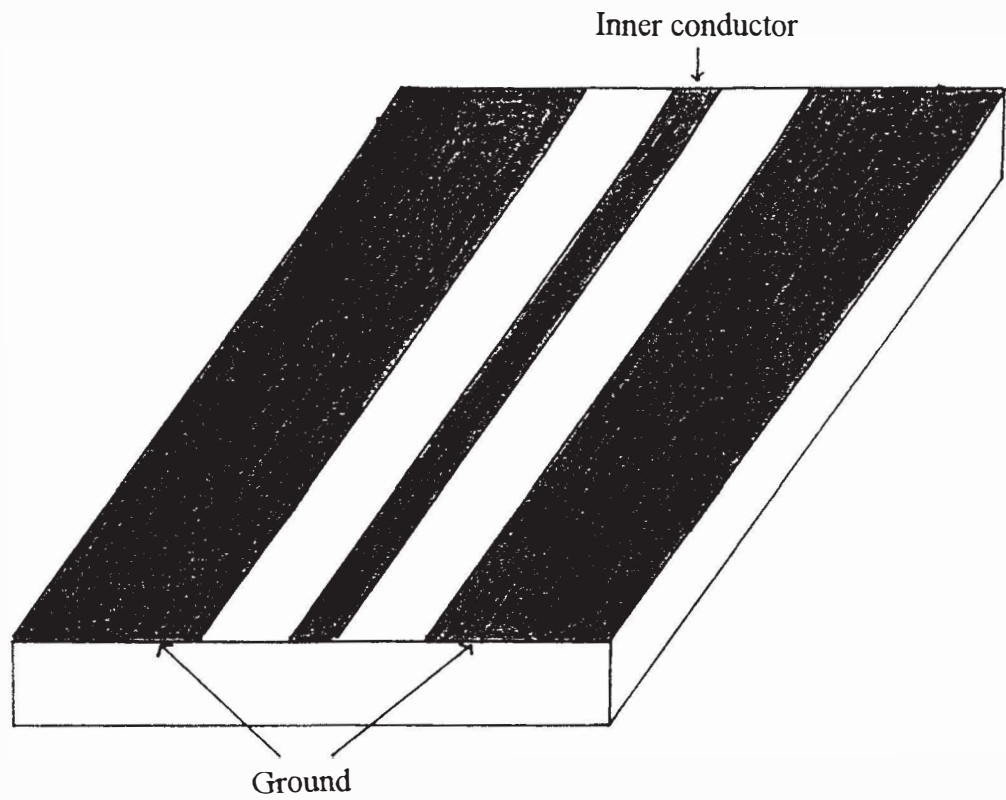


Fig.1.1 Coplanar Waveguide.

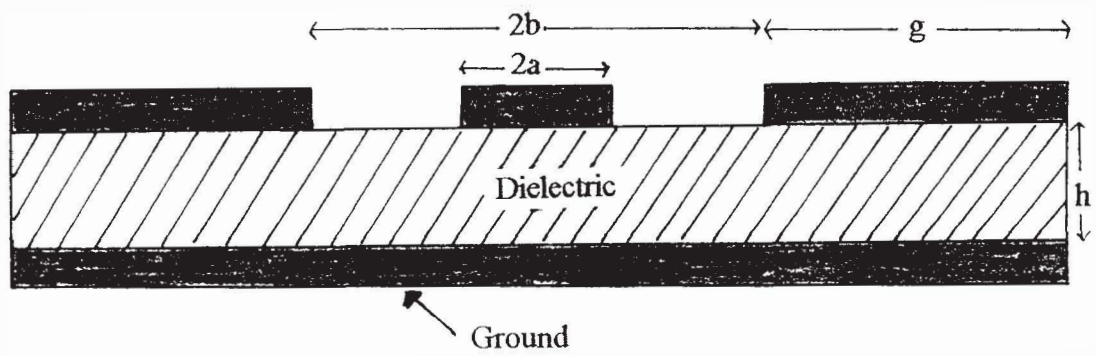


Fig. 1.2 Conductor-backed Coplanar Waveguide.

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. Similarly, h , s , d and f are the height of the substrate, protective layer, test sample and protective layer respectively.

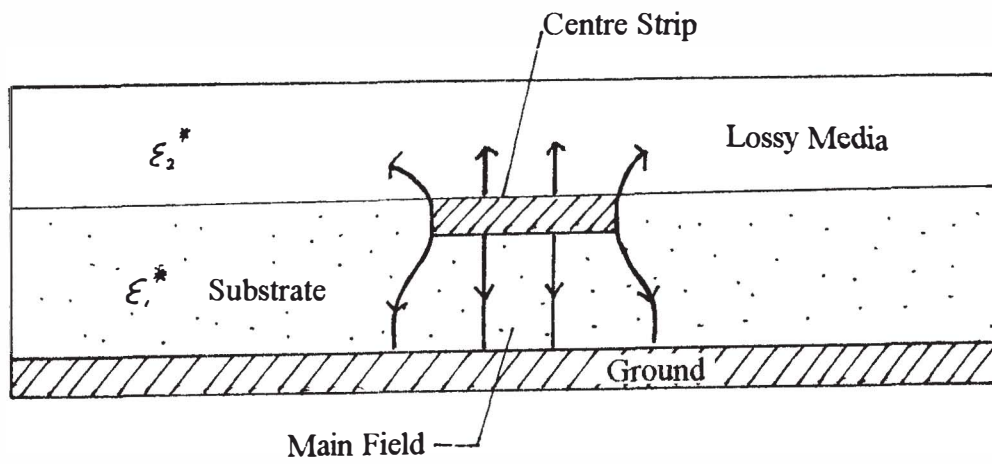


Fig. 1.3 Field Concentration of Microstrip

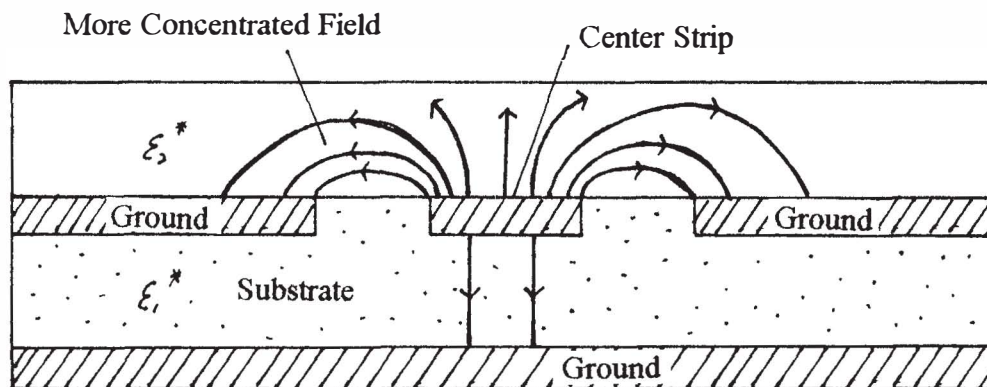


Fig. 1.4 Field Concentration of Conductor-backed Coplanar Waveguide.