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ANALYSIS OF A CONDUTOR-BACKED COPLANAR WAVEGUIDE MOISTURE SENSOR

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ABSTRACT

The analysis of conductor-backed coplanar waveguide moisture sensor by using numerical method is presented. The structure of the sensor is based on the 4-layer system which consists of RT-duriod substrate, protective cover , moist layer and air. The numerical analysis involves with the calculation of effective dielectric constant, characteristic impedance and dielectric loss of the multi-layer structure at various moisture contents with respect to protective layer thickness. A reasonable close agreement between computed and experimental data for attenuation of the sensor at various moisture contents ranging from 30% to 80% (wet basis) of the oil palm fruit has been achieved. This analysis is useful for the prediction of the dynamic range and sensitivity of the sensor by choosing suitable thickness of the protective layer , geometrical parameters and substrate of the sensor.

INTRODUCTION

The structure of Conductor-backed coplanar waveguide (CBCPW) moisture sensor is shown in Figure 1. It consists of three parts, i.e. coupling system representing the transition between coaxial line and coplanar line, coplanar line section and CBCPW sensing area. The cross-section of sensing area is shown in Figure 2. It consists of substrate material, protective cover and wet media. This kind of structure is referred as semi-infinite 4-layer CBCPW.

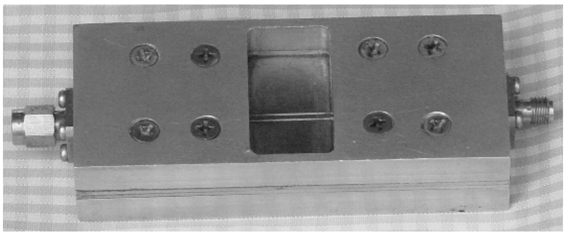

Figure 1: Conductor-backed coplanar waveguide moisture sensor

Before coplanar sensor was introduced, microstrip sensor has been developed [1]. This sensor has been used for measuring moisture content in heave latex [2], oil palm fruits [3], sucrose solutions [1] and various liquids [4].

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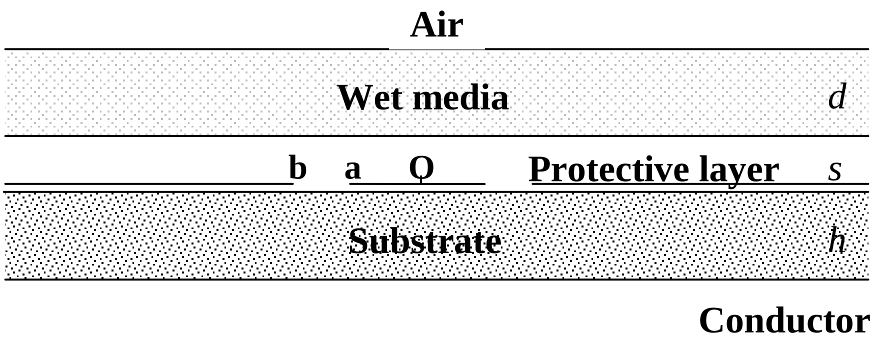

Figure 2: Cross-section of moisture content test structure semi-infinite 4-layer CBCPW moisture sensor.

However it was observed that the sensitivity of the coplanar sensor was substantially better than that of the microstrip sensor. It is on account of the high field concentration between the conducting strip and upper ground plane. Berliner [5] first introduced the coplanar sensor for determination of moisture content in the joints of construction item.
This work describes the quasi-TEM analysis of the multi-layer CBCPW structure, which can be applied for the structure of the sensing area. This analysis deals with the computation on the characteristic impedance, effective dielectric constant and dielectric loss of the sensing area with respect to the variation of the moisture content of the sample. These three parameters are important for the calculation of the reflection and transmission phenomena in the CBCPW moisture sensor. It is essential to analyze the structure in order to predict the dynamic range and sensitivity of the sensor with respect to the gap size and the thickness of the protective layer. This sensor will use the wet sample from oil palm mesocarp as moisture content in this sample varies from 80% in the early fruit and drop to 40% in the matured fruits. This kind of sensor is suitable to determine the quality of fruit that reach the oil palm milling factory.

ANALYSIS OF A 4-LAYER CBCPW

The structure of the sensing area of Figure 2 can be considered as 4-layer CBCPW enclosed by a grounded box where a represents the half width of the conducting strip, (*b*-*a*) is the gap of the coplanar waveguide, *g* is the length of the upper ground and $\varepsilon_{r1}, \varepsilon_{r2}, \varepsilon_{r3}$ and ε_{r4} are the permittivity of the dielectric layers with thickness of *h, s, d* and *f* respectively. The characteristic impedance and the effective dielectric constant of the structure can be calculated from the line capacitance using the numerical method [6]. The propagation mode of this structure is considered to be quasi-transverse electromagnetic wave (quasi-TEM).
The potential $\phi(x, y)$ in each layer of the dielectric is given by Laplace's equation

$$\nabla^2 \phi(x, y) = 0 \qquad (1)$$

This equation has a solution expanded in a Fourier series as

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$$\phi(x,y)=\sum_{i=1}^{\infty} A_i \cos(k_i x)\ \sinh(k_i y)+B_i\ \cos(k_i x)\ \cosh(k_i y) \qquad (2)$$

When the distributed line capacitance per unit length C and C_a are evaluated for the loaded and air-spaced dielectric layer respectively, the real effective dielectric constant ε_{eff} and characteristic impedance Z_o can be obtained from

$$\varepsilon_{eff}=\frac{C}{C_a} \qquad (3)$$

and

$$Z_o=\frac{1}{v\sqrt{C_a C}}, \qquad (4)$$

where v is the velocity of electromagnetic propagation in vacuum.
The capacitance per unit length of the inner conductor to the ground is calculated by integrating the normal components of the displacement field on a Gaussian surface enclosing the inner conductor [6].

$$C=\varepsilon_o \oint_s \varepsilon_r E\cdot dS=-\varepsilon_o \oint_s \nabla\phi\cdot dS \qquad (5)$$

Carrying out the surface integration leads to

$$C=-\ 2\varepsilon_o \sum_{i=1}^{N} A_i^{'}\ \sin\ k_i\,\frac{(a+b)}{2}\{V\} \qquad (6)$$

where

$$A_i^{'}=-\ A_{4i}\left\{\frac{\varepsilon_{r4}}{\varepsilon_{r2}}S_s K_d+\frac{\varepsilon_{r3}}{\varepsilon_{r2}}S_s S_d T_f+\frac{\varepsilon_{r4}}{\varepsilon_{r2}}K_s S_d+K_s K_d T_f\right\} \qquad (7)$$

and

$$\{V\}=\frac{\begin{bmatrix}\varepsilon_{r1}\varepsilon_{r3}\varepsilon_{r4}C_d C_h C_f+\varepsilon_{r1}\varepsilon_{r3}^2 C_h+\varepsilon_{r1}\varepsilon_{r2}\varepsilon_{r4}C_s C_h C_f\\ +\varepsilon_{r1}\varepsilon_{r2}\varepsilon_{r3}C_s C_d C_h+\varepsilon_{r2}\varepsilon_{r3}\varepsilon_{r4}C_s C_d C_f+\varepsilon_{r2}\varepsilon_{r3}^2 C_s\\ +\varepsilon_{r2}^2\varepsilon_{r4}C_f+\varepsilon_{r2}^2\varepsilon_{r3}C_d\end{bmatrix}}{\left[\varepsilon_{r3}\varepsilon_{r4}C_f C_d+\varepsilon_{r3}^2+\varepsilon_{r2}\varepsilon_{r4}C_f C_s+\varepsilon_{r2}\varepsilon_{r3}C_s C_d\right]}, \qquad (8)$$

where

$S_s=\sinh(k_i s)\ \ K_d=\cosh\ (k_i d), S_d=\sinh\ (k_i d), T_f=\tanh\ (k_i f), K_s=\cosh(k_i s)$,
$S_h=\sinh\ (k_i h)\ K_h=\cosh(k_i h), K_f=\cosh(k_i f), S_f=\sinh\ (k_i f), C_d=\coth(k_i d)$,
$C_f=\coth(k_i f)\ C_s=\coth(k_i s)$

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$d = h_3 - h_2$, $s = h_2 - h_1$, $h = h_1$, $f = h_4 - h_3$

If the Fourier sums are truncated at $i = N$, the problem is to find the *N* unknown A_i's. To accomplish this, *x* chooses to be *N* discrete values.

$$x_j = \frac{jl}{N+1} \qquad j = 1, 2, 3, ..., N \tag{9}$$

$\phi(x, y)$ for $a < x < b$ can be written as a $N \times N$ matrix equation

$$\sum_{i=1}^{\infty} m_{ji} A_i' = d_j , \tag{10}$$

where

$$m_{ji} = \begin{cases} k_i \cos(k_i x_j) \ \{V\} & a < x < b \\ \cos(k_i x_j) & x_j \geq b \ or \ x_j \leq a \end{cases} \tag{11}$$

and

$$d_j = \begin{cases} 0 & x_j > a \\ 1 & x_j \leq a \end{cases} \tag{12}$$

Using the previous relationship and with tan $\delta << 1$, dielectric loss, α_d in db/meter for the semi-infinite 4-layer CBCPW structure which represent the sensing area of Figure 2, can be written as [7].

$$\alpha_d = \frac{27.3 f_0}{v\sqrt{\varepsilon_{eff}}}\left[q_1 \tan\delta_1 \varepsilon_{r1} + q_2 \tan\delta_2 \varepsilon_{r2} + q_3 \tan\delta_3 \varepsilon_{r3} + q_4 \tan\delta_4 \varepsilon_{r4}\right], \tag{13}$$

where q_1, q_2, q_3 and q_4 are the dielectric filling factors and f_0 is the operating frequency. These dielectric-filling factors can be determined by transforming the structure in Figure 2, a semi-infinite 4-layer CBCPW to a semi-infinite 3-layer CBCPW. Both structures have the same effective dielectric constant, ε_{eff} [8]. By repeating the above procedure the dielectric loss, α_d can be calculated for the other structures.

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RESULTS AND DISCUSSIONS

This analysis deals with the evaluation of variation of characteristic impedance, effective dielectric constant and dielectric loss of the semi-infinite 4-layer CBCPW with moisture content of the samples. Following the previous recommendations [7], the number of the terms in the Fourier expansion, *N* and the size of the sidewall, *g* is 100 and 10b respectively.

The dielectric properties of the sample at various moisture contents at frequency of about 10.7 GHz and temperature of 26^{o}C are obtained from the mixture model and confirmed with experimental results [9]. On average the dielectric properties of mesocarp varies from ε_{r3} = 48.3 - j 26.7 in the young fruit (85% MC) to ε_{r3} = 10.8 – j 5.0 in the ripe fruit (30% MC). The geometrical and dielectric parameters used in the calculation are shown in table 1**.**

Figures 3 a, b and c show the calculated effective dielectric constant, characteristic impedance and dielectric loss of semi-infinite 3-layer CBCPW as function of the moisture content in the sample respectively and at different thickness of the protective layer.
Generally all figures show that ε_{eff}, Z_o and dielectric loss are drastically affected by the thickness of protective layer and the sensitivity to the moisture decreasing as the thickness of the protective layer increases. At a particular thickness of protective layer, the Z_0 is decreasing with moisture, for example at s/h = 0.06 the impedance drop from 45 ohms at 40% MC to about 38 ohms at 80% MC. However, the decrement in Z_0 is decreasing as the thickness of protective layer increases.

The profile of the effective dielectric constant and the dielectric loss with the moisture content is almost similar and both are increasing as moisture content increases. It is clear from the graphs that the thickness of the protective layer plays an important role controlling the dynamic range and the sensitivity of the sensor. In the range of moisture content between 30% to 80% and the length of the sensor 1.6cm, the sensitivity of the sensor for s/h = 0.06 is about 0.15 dB / % MC while for s/h = 0.22, it is drastically dropped to 0.04dB / % MC.

The analysis of multi-layer CBCPW structure has been used to predict the attenuation of the whole structure of the sensor. The reflection and transmission phenomena in the structure are presented by using signal flow graph and can be simplified by using non-touching loop-rules and the detail is given by Khalid et al [10]. Figure 4 shows the comparison between theoretical and experimental results for s/h = 0.11 and a close agreement between both results has been achieved. As we compared the performance of the CBCPW moisture sensor with the microstrip sensor [11] for the same application, it was found that the sensitivity of the later is lower, with a sensitivity value of 0.35

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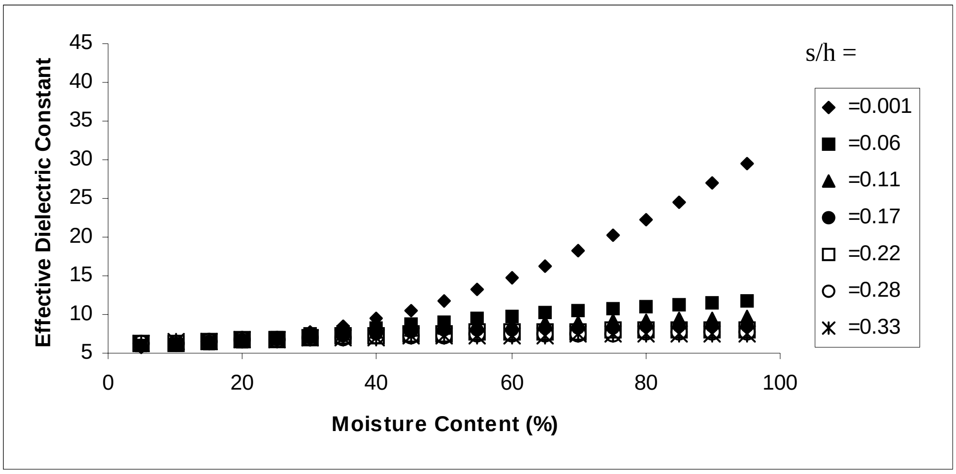
dB/cm/%MC while for the CBCPW sensor the sensitivity was 0.47 dB/cm/%MC. In this comparison, both sensors are without the protective cover (s/h=0).

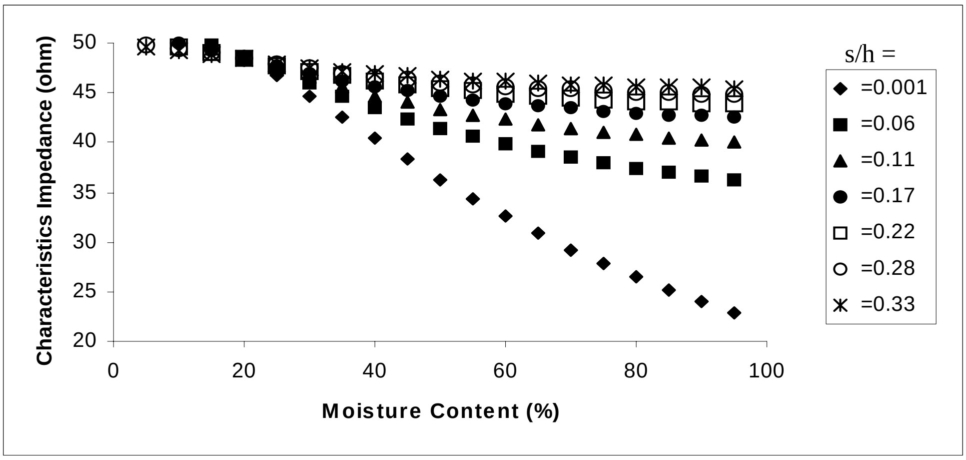
CONCLUSIONS

The analysis of multi-layer CBCPW structure for moisture sensor applications has been discussed. This analysis is useful for the prediction of the dynamic range and sensitivity of the sensor by choosing suitable thickness of the protective layer.

A reasonable close agreement between computed and experimental data for the attenuation of sensor at various moisture contents gives the possibility for the development of a complete optimization program for selecting the geometrical and electrical parameters of the sensor.



(a)



(b)

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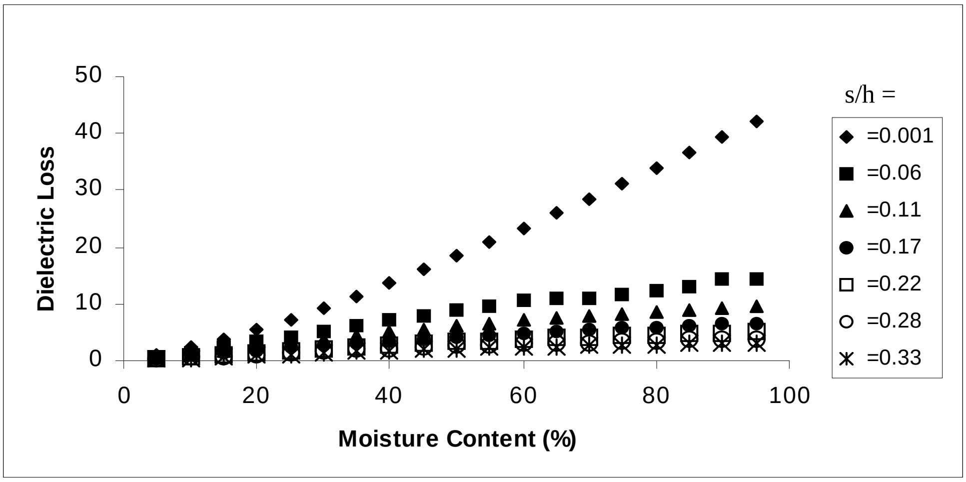

(c)

Figure 3: Variation of (a) effective dielectric constant (b) characteristic impedance (c) dielectric loss with moistcontent of semi-infinite 3-layer CBCPW 10.5 GHz for different ratio of s/h.

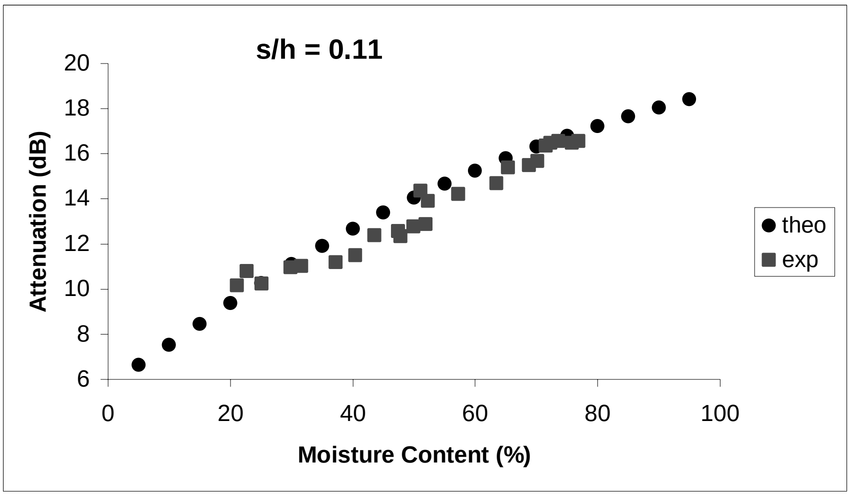

Figure 4: Comparison of Theoretical and Experimental Results of Attenuation at 10.5 GHz. s/h = 0.11

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Table 1: Dielectric and geometrical parameters of the sensor

Dielectric Parameters	**Geometrical Parameters**
Substrate: RT- Duriod	$\left(\frac{b-a}{h}\right) = 0.4$
$\varepsilon_{r1} = 10.5 - j\,0.002$	$\frac{a}{b} = 0.47$
Protective layer: polyethylene	Length of the sensor: l = 1.6cm
$\varepsilon_{r2} = 2.3 - j\,0.003$	

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