Optimum Design of a Microstrip Ring Resonator Sensor to Determine the Moisture Content in Oil Palm Fruits and Seeds

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Oil palm fresh fruit bunch (OPFFB) is the main export product of the oil palm industry. A good oil palm is between 17 to 18 weeks of age with full fruitless maturity. An automated detection system should be implemented to determine the OPFFB's maturity and expedite the harvesting process. Various automated detection methods have been proposed for conventional method replacement. In a preliminary study, a new oil palm fruit sensor was proposed for detecting the maturity of OPFFB, and a microstrip ring resonator was designed for determining the moisture content in oil palm fruit. The coaxial feeder of the microstrip ring was a Sub-Miniature A (SMA) stub contact panel with outer and inner conductors of 4.1 mm and 1.3 mm, respectively. The measurement system consisted of a sensor and a PC controlled network analyzer. This system was tested successfully on seeds and fruits of oil palm with various degrees of maturity. The microstrip ring resonator operated between 2.2 and 3 GHz and required low frequency that enabled the electromagnetic field in the first half of the ring resonator to be transferred to the second half and subsequently cause the collinearity of the maximum field points in the feed lines and resonator.

Keywords: Oil palm; Microstrip ring; Microwave; Network analyzer; Moisture content

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INTRODUCTION

The Malaysian oil palm industry started modestly 70 years ago. Oil palm is currently the largest industry in the sector of agricultural plantation. The total area of oil palm agriculture is over 2.65 million ha, which annually produces over 8 million tons of oil. The oil constitutes 10% of the total biomes produced in the plantation. For maximum palm oil extraction from the mesocarp, oil palm fresh fruit bunch (OPFFB) harvest is expected to be done at the right maturity stage (Dinah *et al*. 2015; Cheng *et al*. 2016a). The oil palm fruit is made up of 3 layers: the skin, which is called mesocarp, the palm oil containing outer pulp, which is called mesocarp, and the hard kernel enclosing shell (endocarp), which is also called the endosperm because it contains both the embryo's reserves for carbohydrates and oil.

Approximately two weeks after anthesis (WAA), fruit development begins. At roughly 12 WAA, the deposition of oil in the endosperm starts and reaches near completion by 16 WAA (Ngalle *et al*. 2014). Within this period, the hardening of the endocarp and endosperm slowly takes place. The hard shell of endocarp encloses the kernel (hard-white endosperm) by 16 WAA. By approximately 15 WAA, the mesocarp oil deposition begins. The mesocarp starts at approximately 15 WAA and continues until about 20 WAA when the fruit is fully matured. Due to slight pollination time variation, the fruit of oil palm does not simultaneously mature on the bunch (Sundram *et al*. 2003).

The approach adapted in Malaysia for the inspection of OPFFBs maturity and fruit classification for harvesting is human expert grading. The fruit's surface color and the number of loose fruit that drops from the bunches depend on the determination of human experts (Kassim *et al*. 2012; Zia *et al*. 2013). The accuracy of this practiced method of grading is very low. Moreover, there is a high probability of different grading results among different human graders. The method of human grader visual inspection is time-consuming and leads frequently to considerable profit losses (Wan *et al*. 2011; Chong *et al*. 2017). Thus, an automated system of fruit grading should be implemented. The ideal automated system of fruit grading would be reliable, accurate, and rapid (Saeed *et al*. 2013; Bahadi *et al*. 2016).

Malaysian researchers have proposed and tested different automated systems of fruit classification. The most common method is the system of color vision, which utilizes a digital camera that is advanced for OPFFB picture collection with computer analysis (Saeed *et al*. 2012; Misron *et al*. 2014). Classifications of OPFFBs are commonly carried out by using a system of artificial intelligence with a color vision system (Fadilah *et al*. 2012, Hazir *et al*. 2012a). Red Green Blue (RGB) space assessment is another common system of color vision. This method of assessment utilizes spectral analysis, which is dependent on various wavelengths of blue, green, and red colors of the image captured (Alfatni *et al*. 2008). In this method, the image color quality is very important. However, the main setback of this method is that indoor performance is advised (Harun *et al*. 2014).

Another method of grading assessment of the oil palm is moisture content (*M.C*). The *M.C* of oil palm fruit mesocarp affects the fruit's weight and surface color to a major extent. The quality of palm oil is closely related to *M.C* in fruits and fruit maturity. When the oil palm fruit matures, the oil content reaches the maximum, whereas *M.C* reaches the minimum (30% *M.C*) in the fruit (Barcelos *et al*. 2015; Tripathi *et al*. 2017). Thus, in mesocarp, the close relationship between the oil content and moisture allows using *M.C* as a gauging parameter for the harvest time and maturity of the mesocarp. A microwave sensor for moisture is used in this method. The procedure is time consuming and relatively complicated (Shete *et al*. 2013; You *et al*. 2014).

Various microwave sensors, such as the coplanar sensor (Cheng *et al*. 2016b), rectangular dielectric waveguide, microstrip sensor (Pongsuwan *et al*. 2014; Jain *et al*. 2016), open-ended rectangular waveguide (Staszek *et al*. 2018), and monopole (Hazir *et al*. 2012b) are used for the estimation of the maturity of oil palm fruits. The first method involving sensors for successful estimation of the *M.C* was carried out using attenuation measurements based microstrip and coplanar sensors. Unfortunately, the fruit sample preparation is very time consuming. First, the oil palm fruit's fresh mesocarp is separated from the nut. Then, the mesocarp is crumbled for the formation of a semi-solid sample.

This study describes the development of a microstrip ring resonator for determining *M.C* in oil palm seeds and fruits. A sensor in the form of a microstrip resonator and a vector network analyzer (VNA) comprises the measurement system. The development of this measurement software was to control and collect data from the VNA using Agilent Visual Engineering Environment Software. To create an electromagnetic field between the fruit sample and the resonator, the microstrip ring resonator was made to operate between 2.2 to 3 GHz and at a low frequency of microwave. A theoretical analysis was conducted to establish the optimum frequency of operation on the basis of frequency and admittance of the microstrip ring. The transverse mode of propagation of electromagnetic wave was assumed. Using standard oven drying, the actual *M.C* was determined. An equation that established the relationship between the predicted and the measured values of the magnitudes (dB) of S_{11} and S_{21} was used for the calibration.

EXPERIMENTAL

Experimentation planning included the selection of samples, fabrication and construction of the microstrip ring sensor, measurement set-up, as well as *M.C* and reflection measurements.

Selection of Samples

OPFFBs were obtained from Ulu Langat Oil Palm Mill, Dengkil, Malaysia. Forty samples were selected from the unripe and ripe categories. The sample selection was carried out based on the standard specifications such as fruit's age and surface color as set by the Malaysian Palm Oil Board. The unripe seed samples selected were dark purple in color, while the color of the ripe seed samples was orange, as shown in Fig. 1. Unripe seed samples were selected 6 WAA to 7 WAA, and ripe seed samples were selected after 17 WAA to 18 WAA (Harun *et al*. 2013). More than 40 fruit samples and more than 40 seed samples were selected, thus allowing the selected sampling to range from 25% to 95% MC. The individual palm fruits are approximately 2 to 5 cm long and weigh approximately 6 to 20 gm per fruit. The shape of fruit is almost spherical, ovoid, or elongated in shape

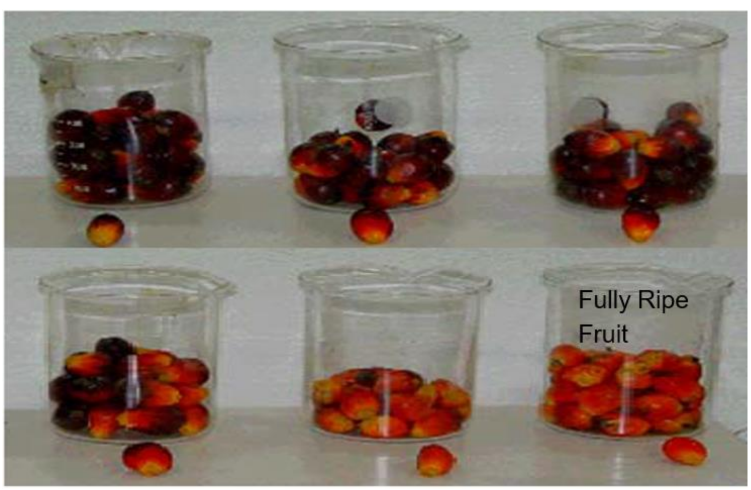


Fig. 1. Various maturity stages of oil palm fruits

Microsoft Office 2010 software was used to design the microstrip ring by specifying numerous dimensions, such as thickness, height, width, dielectric constant, and characteristic impedance of 50 Ω. The microstrip ring was designed with a width of 1.1552 mm and a characteristic impedance of 50 Ω on substrate (height h = 787.4 μm, dielectric constant ε_r = 2.2, inner radius Ri = 5 mm, outer radius Ro = 6.5776, coupling gap S = 1 mm, and microstrip width w = 1.1552 mm). The corresponding w/h and s/h ratios were 1.467 and 1.27 mm, respectively, where w is the width of the microstrip, and S is the spacing between the ring and feedline, as shown in Fig. 2.

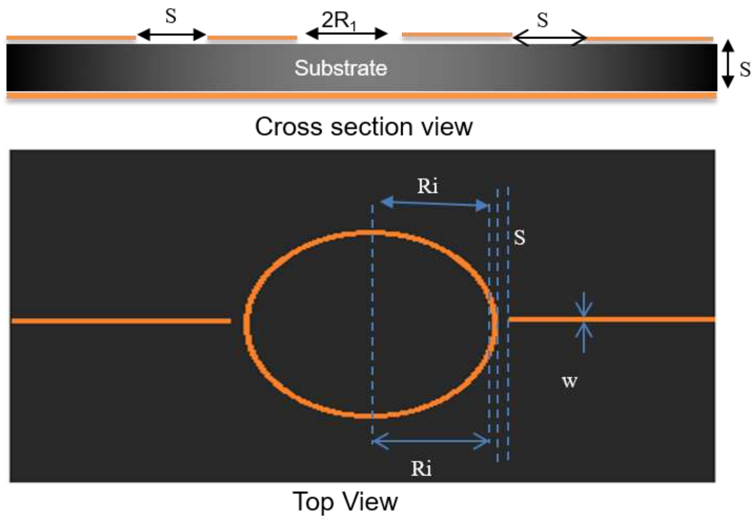


Fig. 2. Geometry of microstrip ring resonator shown in cross-section and top views (not to scale): R_i, inner radius; *Ro*, outer radius; *S*, coupling gap; *w*, width of microstrip; and *h*, substrate height

Measurement Set-up

The measurement setup shown in Fig. 3 consists of a computer controlled HP8720B VNA and a 2-port microstrip ring. A computer program was developed using Agilent VEE to control and acquire the data. All microwave measurements were conducted using VNA with a frequency range between 2.2 GHz and 3 GHz. VNA was calibrated by implementing a standard full two-port calibration technique. In the measurement, four *S*-Parameters, such as S_{11}, S_{12}, S_{21}, and S_{22}, were found to be associated with VNA. S_{11} and S_{22} were involved for reflection measurements, which measure the reflection coefficient magnitude and phase, standing wave ratio, and return loss or impedance. S_{21} and S_{12} were involved for transmission measurements, which measure the transmission coefficient, insertion loss, gain loss, and group delay or electrical delay.

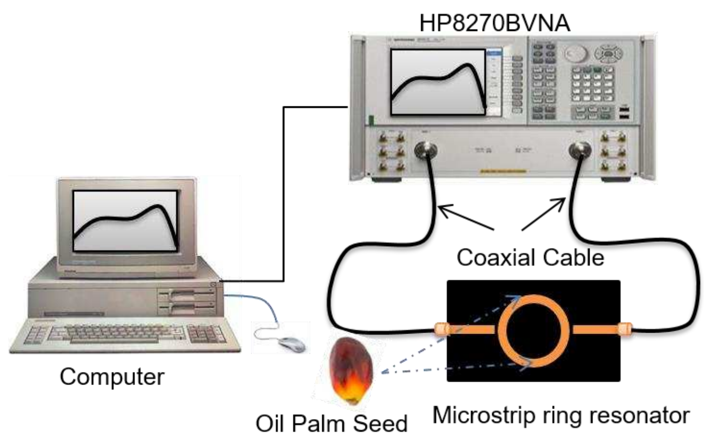


Fig. 3. Measurement setup with HP8720B VNA, a microstrip ring, a coaxial cable, and Agilent VEE in the computer

This study involved two measurements. The first measurement was for the fruit samples of oil palm, and the second measurement was for the seed samples of oil palm fruit. The gap between the fruit and sensor was minimized to obtain accurate results. The samples were pressed gently to allow the surface in contact with the microstrip ring to be flat and to ensure that no gap existed between the fruit and sensor. All microwave measurements of fruit samples were conducted at (25 ± 2) °C. The samples were then dried in a forced-air oven for 2 days to 3 days at 100 °C for *M.C* determination on a wet basis.

Moisture Content (*MC*) Measurements

The *M.C* of materials is an important parameter in many studies and industrial applications, including food and agriculture-related industries. The actual *M.C* of the fruit sample was determined by the standard oven drying method (Yahaya *et al*. 2014), formerly called the Palm Oil Research Institute of Malaysia test method. Before drying, the single fruit sample was weighed using a digital scale, and its value was recorded. The temperature in the oven must be above or equal to the temperature of boiling water but lesser than the temperature of boiling oil because the objective of this method is to remove water in the sample and to maintain other important components, such as oil and fiber, in the oil palm fruit. The fruit sample was dried at (103 ± 2) °C in the oven for 2 days to 3 days. During drying, the fruit was removed, cooled, and re-weighed once a day to ensure that the weight of the fruit reached a constant level. The relative *M.C* of oil palm fruit in percentage (wet basis) was calculated by Eq. 1,

$$M.C\% = \frac{M_{wet} - M_{dry}}{M_{wet}} \times 100\% \tag{1}$$

where M_{wet} and M_{dry} are the weights of the fruit sample before and after drying in the oven, respectively. The weight of the fruit nut is accounted for in the calculation.

Theoretical Background

The dielectric properties of oil palm fruits vary predominantly with moisture content, density, and structure of the fruits. Therefor the high correlation between fruits permittivity and that of water content of the fruits leads the usage of microwave method in sensing moisture content (Abbas *et al*. 2005).The effective complex relative permittivity of oil palm fruits can be approximated from the permittivity of constituents by using the mixing formulas. The most useful and general structure-independent mixing formula is expressed

$$(\varepsilon_{rm})^A = \sum_i v_i \, (\varepsilon_{ri})^A \tag{2}$$

where ε_{rm} is the effective complex relative permittivity of the mixture, v_i is the volume fraction of the i^{th} constituent with $\sum_i v_i = 1$, and ε_{ri} is the corresponding complex relative permittivity. A is an empirical constant called the degree of the expression $0 < A \leq 1$.

For the two-phase mixture, equation (2) can be written as,

$$\varepsilon_{rm} = [v_1(\varepsilon_{r1})^A + (1 - v_1)(\varepsilon_{r2})^A]^{\frac{1}{A}} \tag{3}$$

If v_i denotes the volume of the suspension occupied by water, then it can be expressed as follows (McKeown *et al.* 2015),

$$v_1 = \frac{M.C(^{g_2}/_{g_1})}{(100 - M.C) + M.C(^{g_2}/_{g_1})} \tag{4}$$

where *M.C* is the moisture content in the mixture and g_1 and g_2 are the specific gravities of water and dry substance, respectively (McKeown *et al*. 2015).

Yeow *et al*. (2010) applied equation (2) in the dielectric modelling of the oil palm mesocarp. As the oil palm fruits consist of three components water, fiber, and oil, thus,

$$\sqrt{\varepsilon_{eff}^{*}} = v_{water}\sqrt{\varepsilon_{water}^{*}} + v_{fiber}\sqrt{\varepsilon_{fiber}^{*}} + v_{0il}\sqrt{\varepsilon_{oil}^{*}} \quad (5)$$

where $\varepsilon_{water}^{*}, \varepsilon_{fiber}^{*}$ and ε_{oil}^{*} are the corresponding complex permittivity of water, fiber and oil respectively.

Therefore, the interaction of the wave with the water and oil molecules increases. Consequently the reflection S_{11} increases and the transmission S_{21} reduces of the wave inside the oil palm fruit. The *S*-parameters of the circuit can be determined based on Eq. 6:

$$S_{11}^2 + S_{21}^2 = 1 \quad (6)$$

In addition, from S_{11} we can obtain S_{21} and vice versa as in Eq. 7:

$$S_{11}^2 = 1 - S_{21}^2 \Rightarrow S_{11} = \sqrt{1 - S_{21}^2}\ ,\ S_{21}^2 = 1 - S_{11}^2 \Rightarrow S_{21} = \sqrt{1 - S_{11}^2}, \quad (7)$$

Theoretically, the value of resonant frequency for narrow rings can be approximated with fair accuracy by assuming that the structure resonates if its electrical length is an integral multiple of the guided wavelength. When a discontinuity is introduced into the ring, the electric length may not be equal to the physical length. This difference in the electric and physical length will cause a shift in the resonant frequency. To calculate the resonance frequency *(f)* of the Microstrip Ring Resonator, the following equations can be applied,

$$\lambda_g = \frac{c}{f\sqrt{\varepsilon_{eff}(f)}} \quad (8)$$

$$f = \frac{c}{\lambda_g\sqrt{\varepsilon_{eff}(f)}} \quad (9)$$

where λ_g are the guided wavelength (m), ε_{eff} the effective permittivity, and c the velocity in free space.

RESULTS AND DISCUSSION

Variation in Magnitudes (dB) of S_{11} and S_{21} with Frequency and *M.C* for Fruit Samples

Figures 4(a) and (b) show the variation in magnitudes (dB) of S_{11} and S_{21} with frequency for the fruit samples in oil palm with different *M.C.* The magnitudes (dB) of S_{11} and S_{21} were approximately and linearly changed with the frequency for all *M.C*. The results also indicated that the magnitudes (dB) of S_{11} and S_{21} changed approximately and linearly with the amount of *M.C* for the fruit samples in oil palm fruits. The percentages of *M.C* were 35.40%, 58.70%, 64.55%, 70.35%, and 91.40%, as shown in Figs. 4(a) and (b). The corresponding mean value │dB│ readings of S_{11} were 0.673, 0.753, 0.968, 1.873, and 2.471dB. The corresponding mean value │dB│ readings of S_{21} were 53.647, 40.740, 36.413, 35.409, and 30.229 dB. From Fig. 4(a), the magnitude (dB) of S_{11} decreased with the increase in corresponding *M.C*; Fig. 4(b) shows that the magnitude (dB) of S_{21} gradually increased with the increase in *M.C*.

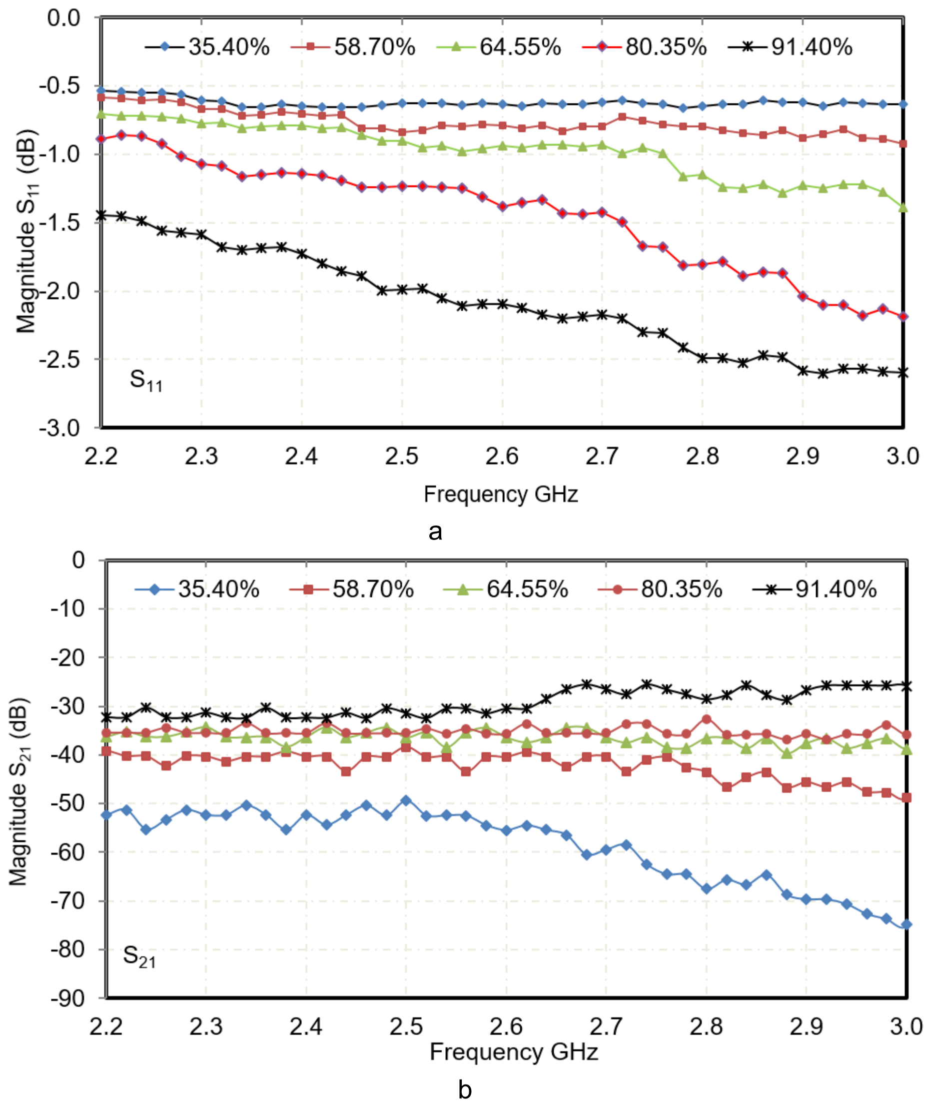


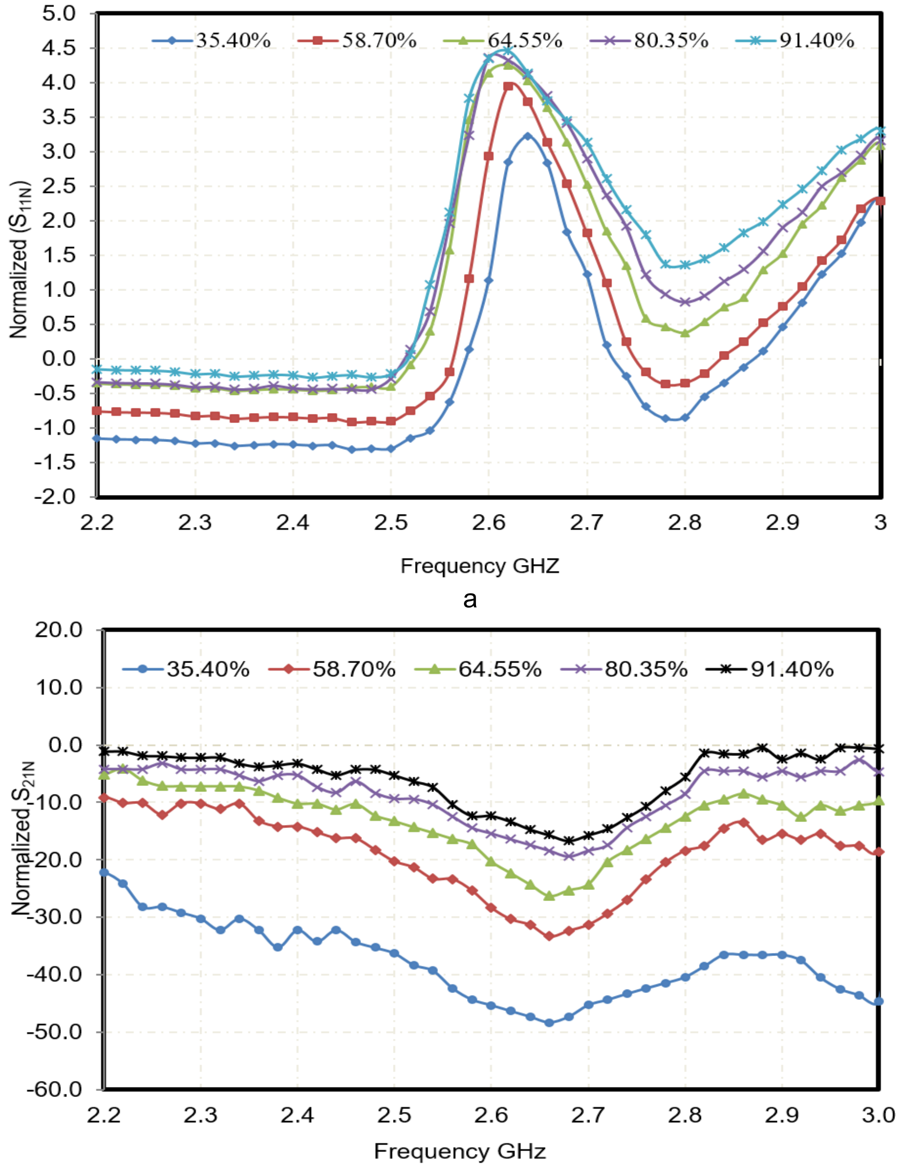
Fig. 4. Variations in magnitudes (dB) of (a) S_{11}, and (b) S_{21} for fruit samples with frequency and MC

Figures 5(a) and (b) show the variations in total magnitude (dB) of S_{11} and S_{21} with frequency ranging between 2.2 GHz and 3 GHz for the fruit samples of oil palm with different stages of *M.C*. The normalized S_{11N} and S_{21N} readings can be calculated using the following equations,

$$S_{11\mathrm{N}} = -20\log\frac{|S_{11}|_{fruit}}{|S_{11}|_{dis-fruit}} \tag{10}$$

$$S_{21\mathrm{N}} = -20\log\frac{|S_{21}|_{fruit}}{|S_{21}|_{dis-fruit}} \tag{11}$$

In Figs. 5(a) and (b), the resonant frequency appeared at about 2.66 GHz theoretically, the resonant frequency should appear at about 2.65 GHz. This finding indicated that the mean relative error between the theoretical and measurement was within 1%.



b

Fig. 5. Variations in normalized (dB) of (a) S_{11N}, and (b) S_{21N} for fruit samples with frequency & MC

Variations in Magnitude (dB) of S_{11} and S_{21} with Frequency and *M.C* for Seed Samples

Figures 6(a) and (b) show the variations in magnitude (dB) of S_{11} and S_{21} with frequency for seed samples of oil palm with different *M.C*. The magnitude (dB) of S_{11} and S_{21} changed approximately and linearly with the frequency for all *M.C* values. The results showed that the magnitude (dB) of S_{11} and S_{21} changed approximately and linearly with the amount of *M.C* for seed samples of oil palm fruits. The corresponding mean value │dB│ readings of S_{11} were 0.596, 0.656, 0.799, 0.9, and 1.436 dB, whereas the corresponding mean value │dB│ readings of S_{21} were 50.729, 42.739, 38.41, 35.403, and 30.274dB. From Fig. 6(a), the magnitude (dB) of S_{11} decreased with the increase in corresponding *M.C*, whereas Fig. 6(b) indicated that the magnitude (dB) of S_{21} gradually increased with the increase in *M.C*.

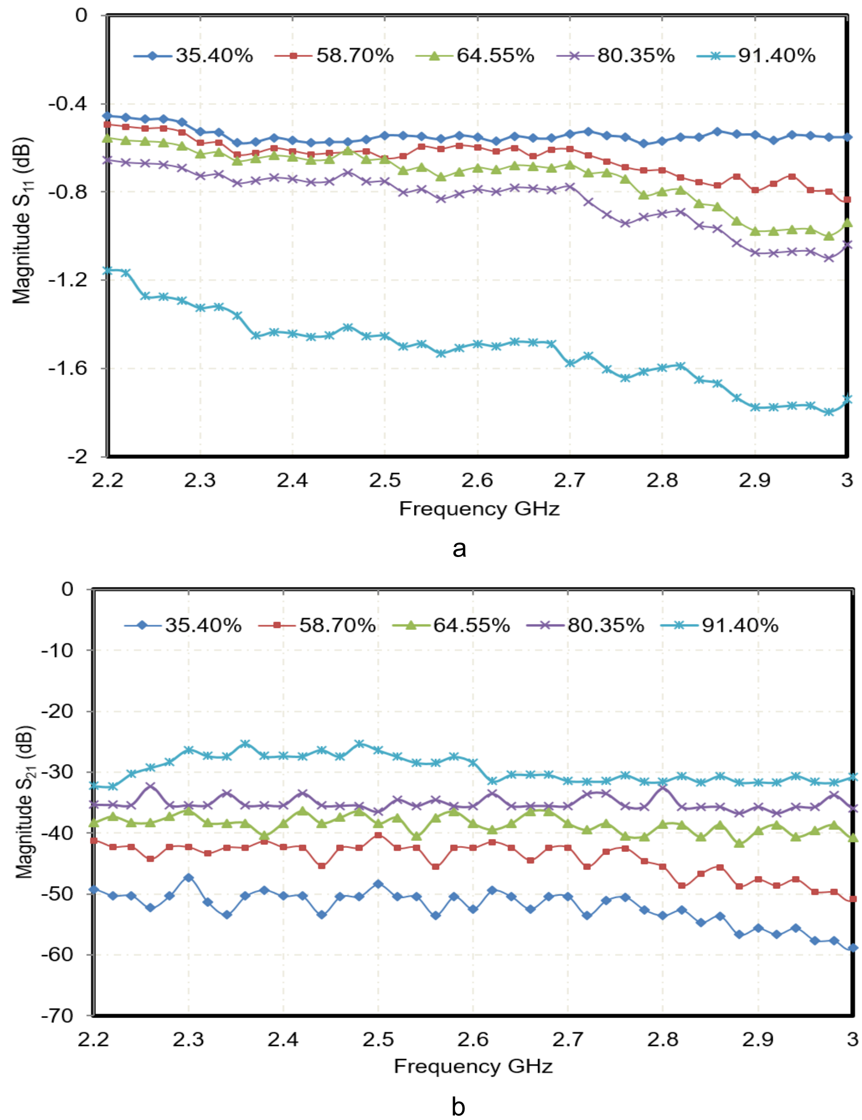


Fig. 6. Variations in magnitude (dB) of (a) S_{11}, and (b) S_{21} for seed samples with frequency & MC

Figures 7(a) and (b) depict the variations in total magnitude (dB) of S_{11} and S_{21} with the frequency ranging between 2.2 GHz to 3 GHz for seed samples of oil palm fruit with different stages of *M.C*. The normalized S_{11N} and S_{21N} readings can be calculated by Eqs. 12 and 13. In Figs. 7(a) and (b), the resonant frequency appeared at about 2.66 GHz.

$$S_{11\mathrm{N}} = -20\log\frac{|S_{11}|_{seed}}{|S_{11}|_{dis-seed}} \tag{12}$$

$$S_{21\mathrm{N}} = -20\log\frac{|S_{21}|_{seed}}{|S_{21}|_{no-seed}} \tag{13}$$

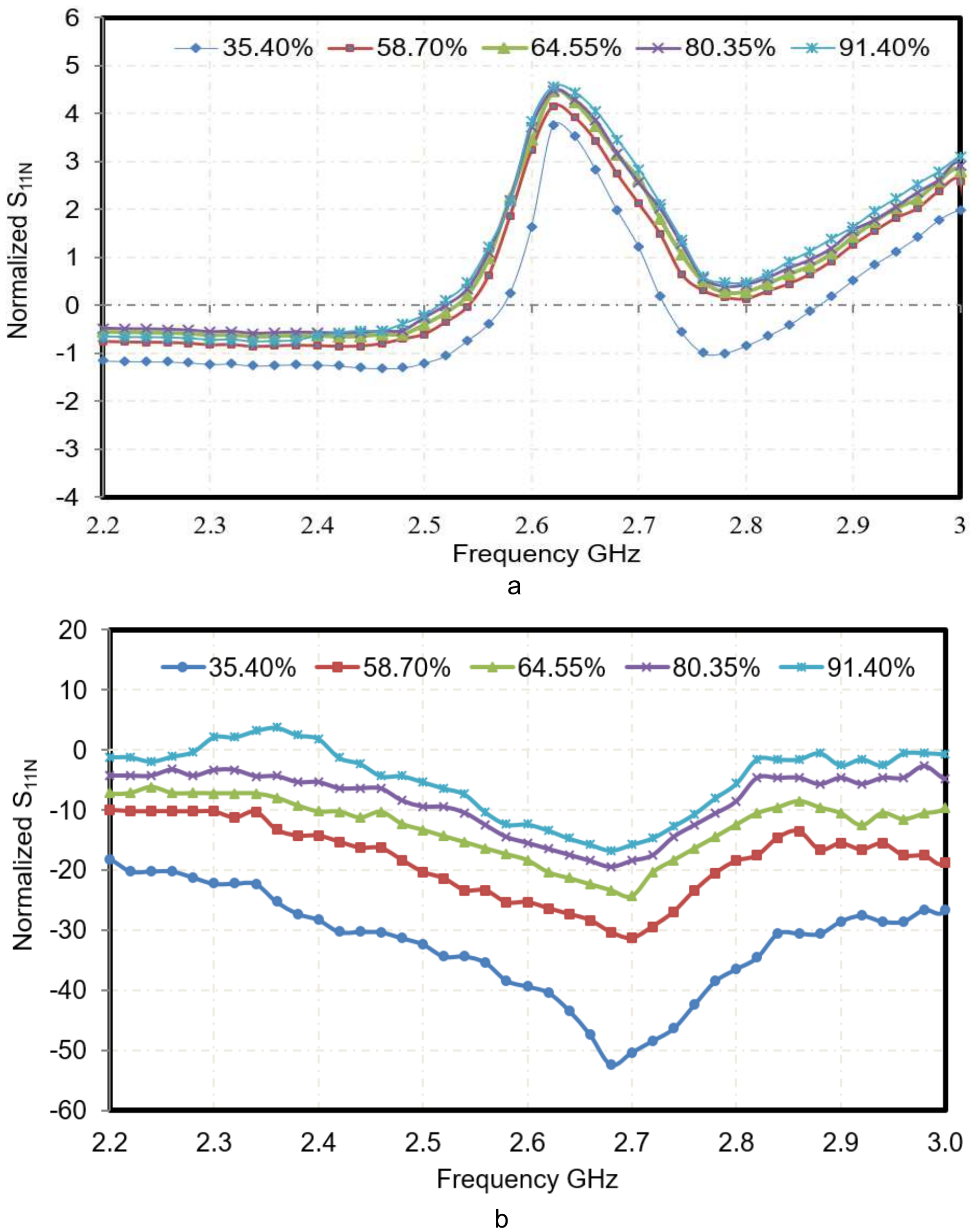


Fig. 7. Variations in normalized (dB) of (a) S_{11N}, & (b) S_{21N} for seed samples with frequency & MC

Relationship between the Magnitude (dB) and *M.C* of Fruit Samples

Figure 8 shows the relationship between the measured magnitude (dB) of S_{11} and S_{21} and $M.C$ with a resonant frequency of 2.66 GHz. The magnitude (dB) varied linearly with the $M.C$ of fruit samples. Thus, the relationship between the measured magnitude (dB) of S_{11} and $M.C$ of fruit samples in oil palm can be represented in Eq. 14.

$$M.C = -0.0225|S_{11}| - 0.0056 \tag{14}$$

Similarly, the relationship between the measured magnitude (dB) of S_{21} and $M.C$ of fruit samples in oil palm can be represented in Eq. 15.

$$M.C = 0.1221|S_{21}| - 38.478 \tag{15}$$

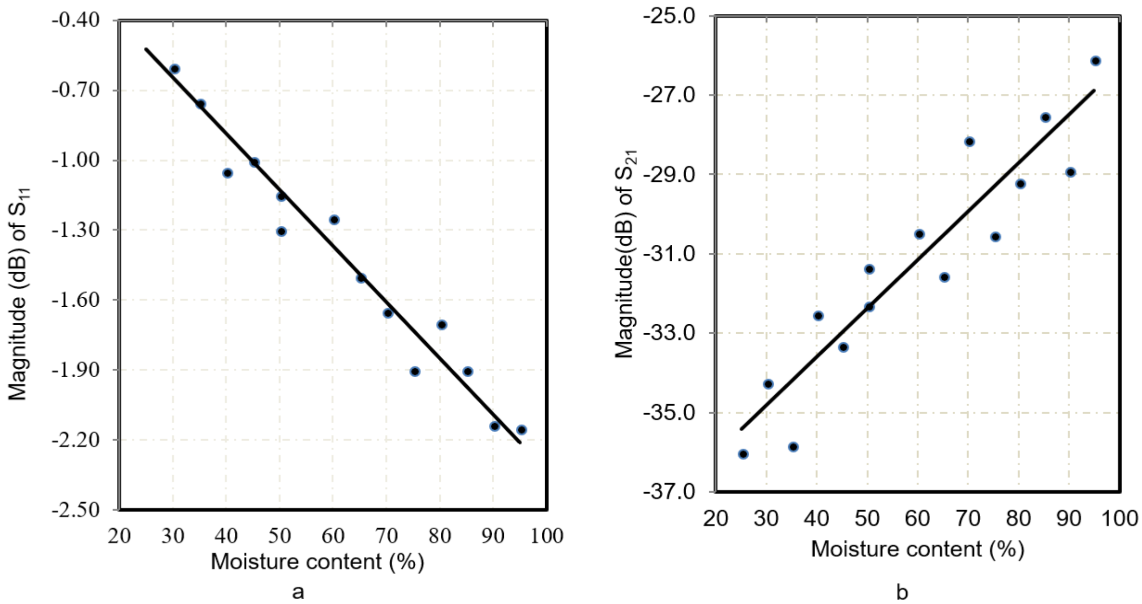


Fig. 8. Relationship between the magnitude (dB) and *M.C* of (a) S_{11} and (b) S_{21} from the fruit samples

Comparison between the Measured and Predicted *M.C* (%) of Oil Palm Fruit Samples

The empirical equation for predicting the amount of moisture content was established as shown in Eqs. 14 and 15. The validation process has been done to validate these equations. The validation was made with new measurements carried out using new (15) sample of oil palm fruit at different moisture contents. Actual moisture contents were found by using conventional oven method. The comparison between predicted and measured moisture contents is shown in [Figs 8(a) and (b)] by Eqs. 14 and 15, respectively. This was followed by the relative error between actual and predicted moisture content. The equations 14 and 15 are valid for low and high values of moisture content and frequency of 2.66 GHz. The errors between actual and predicted moisture content were calculated using the following equation,

$$\text{Mean } error = \frac{\sum_{i=1}^{N}\left|\frac{M.C_{oven} - M.C._{predicted}}{M.C._{oven}}\right|}{N} \tag{16}$$

The percentage of relative error was normally distributed. This means that the moisture contents error was uniformly distributed in oil palm fruits. It was clearly found that the microstrip circular ring sensor has a good performance in terms of the regression coefficient for $|S_{11}|$ and $|S_{21}|$ of $R^2 = 0.9868$, and 0.9788 respectively.

In this study, the mean relative error percentages between the predicted *M.C* obtained from Eqs. 14 and 15 and the actual *M.C* were 2.7% and 2.9% respectively, for the fruit samples as illustrated in Table 1.

Table 1. Relative Error between Standard Oven Drying Methods for Fruit Samples

No of sample	$\frac{M.C_{ovin} - M.C_{predict}}{m.c_{oven}}$	
	S11	*S21*
1	2.5631	1.5325
2	1.2435	4.8626
3	3.3027	3.3656
4	5.8884	2.4650
5	3.4569	7.7739
6	0.8090	0.5327
7	5.8361	0.2312
8	1.0381	1.4169
9	2.5541	4.5954
10	0.3312	6.1233
11	1.4169	2.0866
12	4.5954	3.9147
13	0.5327	0.2078
14	4.4047	1.2435
15	2.5202	3.3027
	Mean error =2.7%	Mean error =2.9%

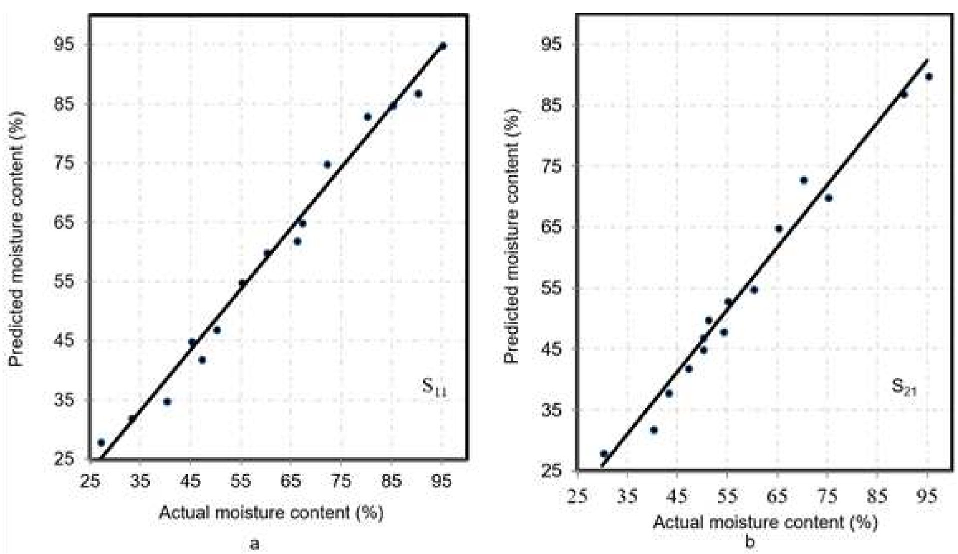


Fig. 9. Comparison between the measured and predicted *M.C* of (a) S_{11} and (b) S_{21} for fruit samples of oil palm

Comparison between the Predicted and Measured Magnitudes (dB) for S_{11} and S_{21} of Fruit Samples

The predicted values of magnitude (dB) of S_{11} and S_{21} were obtained from Eqs. 14 and 15, respectively. Figures 10(a) and (b) show the relationship between the measured and predicted magnitude (dB) of S_{11} and S_{21} for fruit samples of oil palm. The mean relative error percentage between the measured and predicted magnitudes (dB) of S_{11} is 1.50%, and the mean relative error percentage between the measured and predicted magnitudes (dB) of S_{21} is 3.33%.

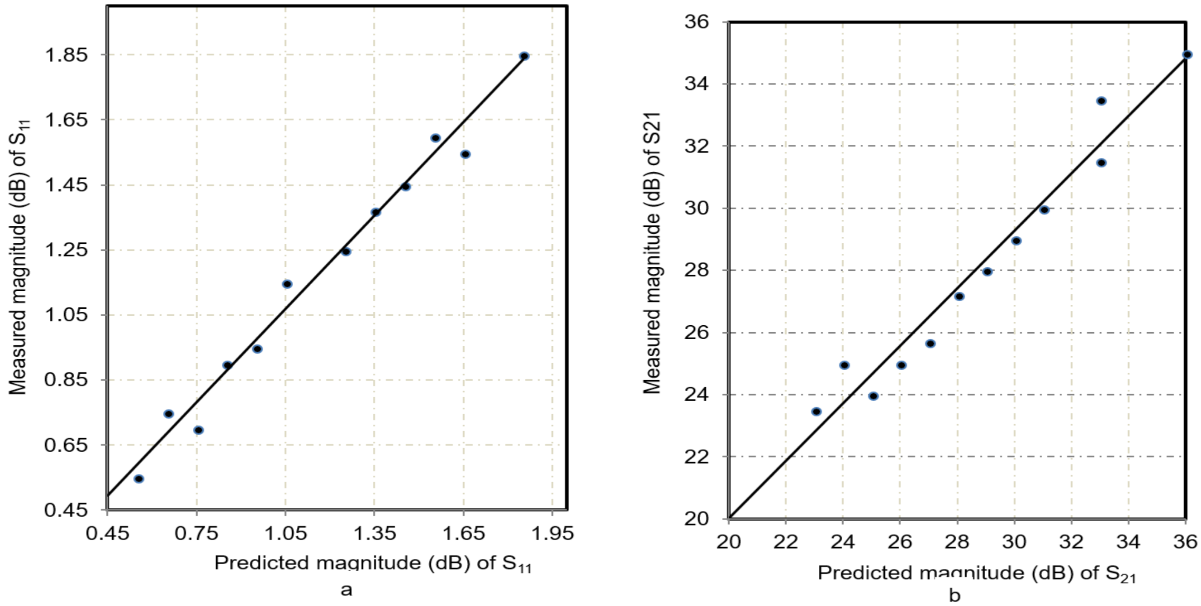


Fig. 10. Comparison between the measured and predicted magnitudes (dB) of (a) S_{11} and (b) S_{21} of fruit samples

Relationship between Magnitude (dB) and *M.C* of Seed Samples

Figure 11 indicated the relationship between the measured magnitudes of S_{11} and S_{21} with *M.C* at a resonant frequency of 2.66 GHz. The results show that the magnitude of S_{11} and S21 changes approximately and linearly with the frequency for all band of moisture content, and also linearly with the amount of moisture content for the seed samples. Thus, the relationship between the measured magnitude S_{11} (dB) and *M.C* of seed samples of oil palm fruit can be represented in the following form:

$$M.C = 0.9577\left|S_{11}\right| + 0.0631 \tag{17}$$

Similarly, the relationship between the measured magnitude S_{21} (dB) and *M.C* of seed samples of oil palm fruit can be represented in the following form:

$$M.C = 0.\ 9234\left|S_{21}\right| - 1.5688 \tag{18}$$

Comparison between the Measured and Predicted *M.Cs* of Seed Samples of Oil Palm Fruit

The predicted *M.C* obtained from Eqs. 14 and 15 were compared with the values of $\left|S_{11}\right|$ and $\left|S_{21}\right|$, and the actual *M.C* values of 15 other seed samples were obtained using the oven drying method with a resonant frequency of 2.66 GHz (Fig. 12). The predicted *M.C* using Eqs. 14 and 15 were in good agreement with the actual *M.C*. The mean relative error percentages between the predicted and measured *M.C*s were obtained by using Eq. 16. In this study, the mean relative error percentages between the predicted *M.C* obtained from Eqs. 14 and 15, and the actual *M.C* were 2% and 2.3%, respectively.

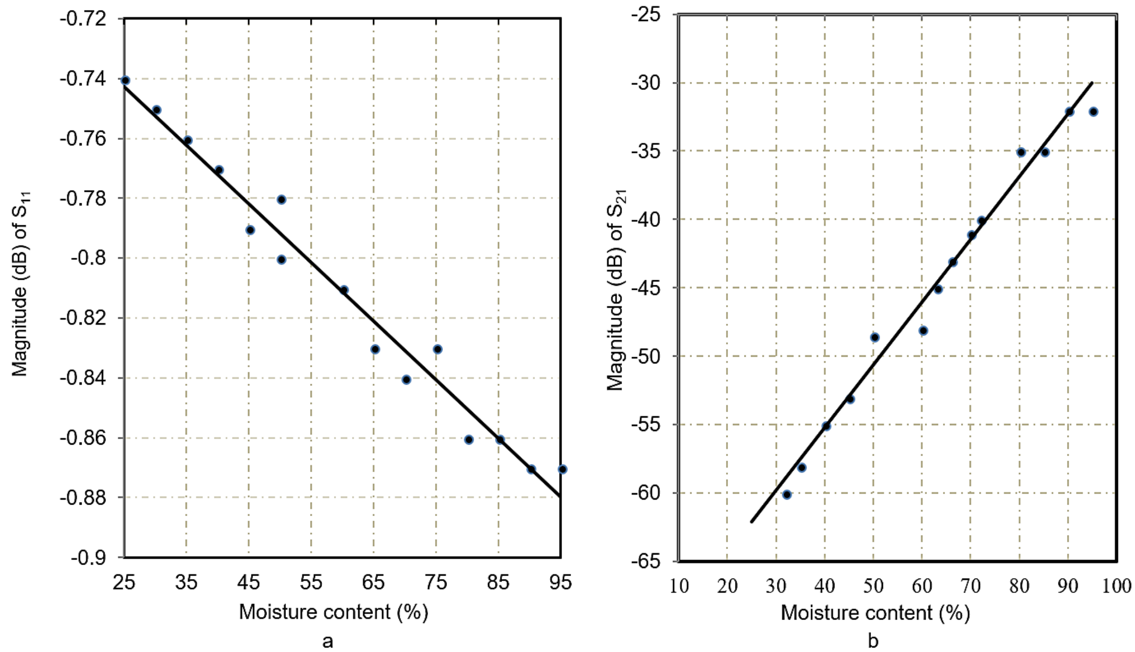


Fig. 11. Relationship between the magnitude (dB) and *M.C* of (a) S_{11} and (b) S_{21} from the seed samples

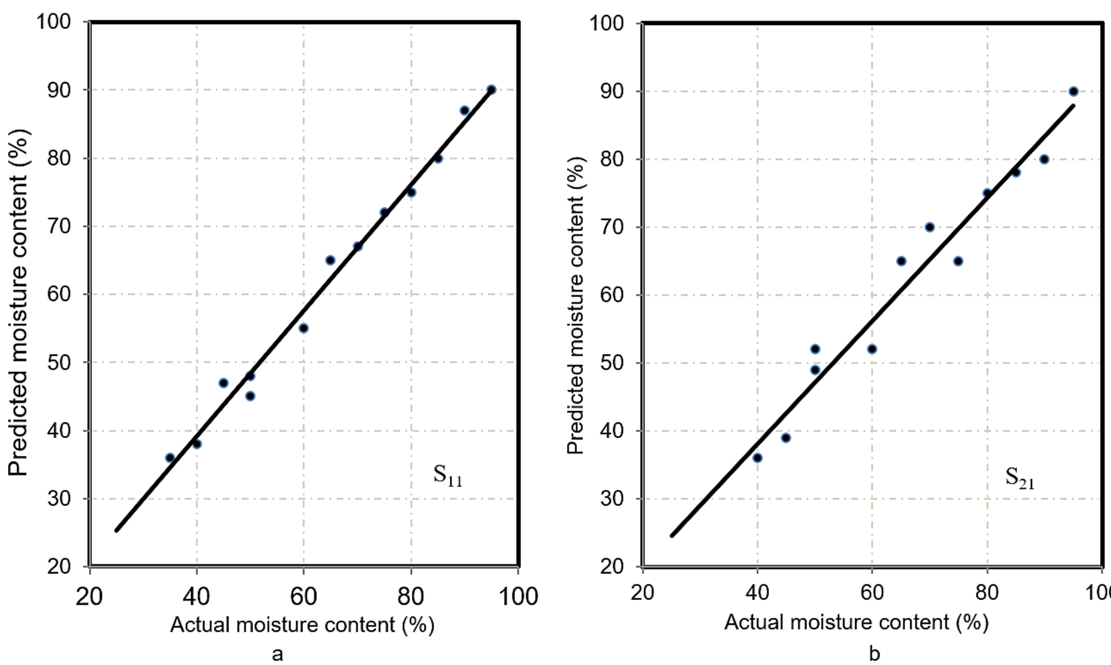


Fig. 12. Comparison between the predicted and actual *M.C*s of (a) S_{11} and (b) S_{21} from the seed samples of oil palm fruit

Comparison between Predicted and Measured Magnitudes (dB) of S_{11} and S_{21} from the Seed Samples

The predicted values of magnitude (dB) of S_{11} and S_{21} were obtained from Eqs. 17 and 18, respectively, when the values of *M.C* were measured. Figures 13 (a) and (b) show the relationship between the measured and predicted magnitudes (dB) of S_{11} and S_{21} from the seed samples of oil palm fruit. The mean relative error percentage between the measured and predicted magnitudes (dB) of S_{11} was 2.70%, and the mean relative error percentage between the measured and predicted magnitudes (dB) of S_{21} was 3.32%.

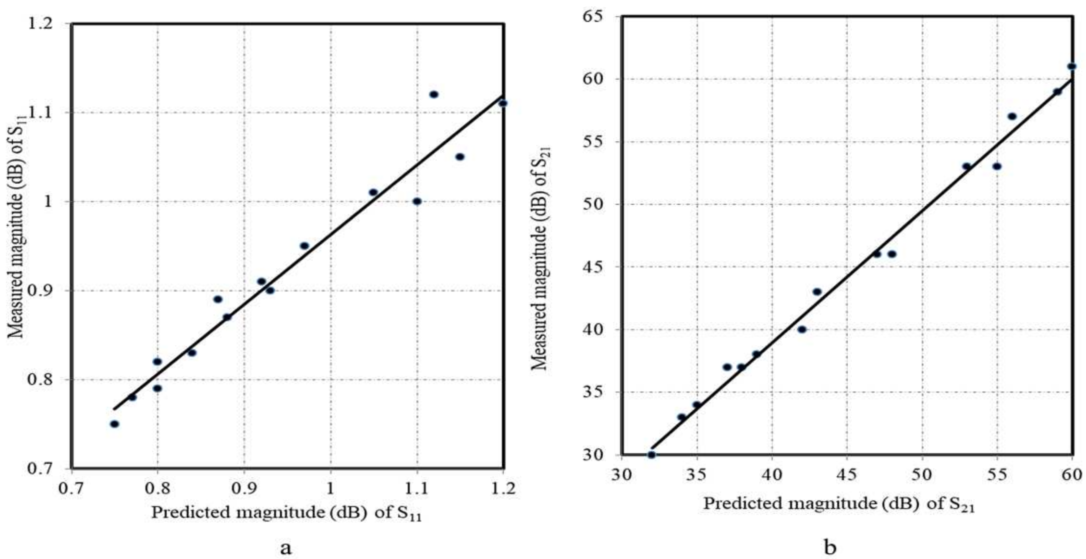


Fig.13. Comparison between the measured and predicted magnitudes (dB) of (a) S11 and (b) S21 from the seed samples

Effect of Fruit Size on Magnitude (dB) of S_{11}

Figure 14 and Table 2 show the relationship between the magnitude (dB) of S_{11} and fruit size at an *M.C* of 70% and a resonant frequency of 2.66 GHz. The magnitude (dB) varied linearly with fruit size, whereas the magnitude (dB) of S_{11} decreased with the increase in fruit size with an *M.C* of 70%.

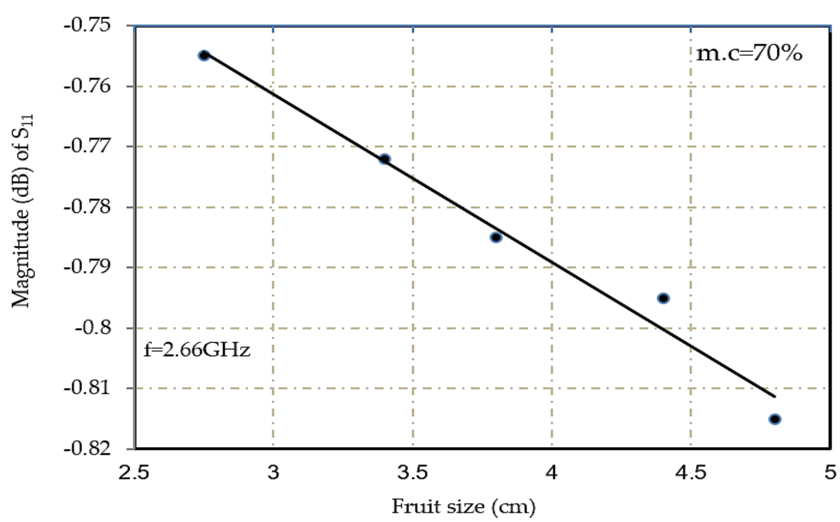


Fig. 14. Relationship between the magnitude (dB) of S_{11} and fruit size with 70% *M.C* and a resonant frequency of 2.66 GHz

Table 2. Relationship Between the Magnitude (dB) of S11 and Fruit Size with 70% M.C and a Resonant Frequency of 2.66 GHz

Fruit size (cm)	Magnitude (dB) of S_{11}
2.7	-0.755
3.45	-0.773
3.8	-0.785
4.4	-0.795
4.75	-0.815

CONCLUSIONS

1. This study successfully developed a low-cost microstrip ring resonator sensor using the microwave measurement technique for the rapid and accurate determination of various percentages of moisture content (*M.C*) of the fruits and seeds of oil palm fruits.
2. The study combined two separate fields of study: the development of a microstrip ring resonator and the moisture measurement of fruits and seeds of oil palm fruits.
3. The microstrip ring resonator is a simple, fast, accurate, and portable method for determining the *M.C* of oil palm fruits and seeds.
4. The microstrip ring can be used for seed/fruit measurement of oil palm fruit and for transmission/reflection measurement.
5. The moisture measurement using the microstrip ring did not require a time-consuming standard oven drying method. In addition, this measurement is suitable for a rapid and first quality check of fruit maturity.

ACKNOWLEDGMENTS

The authors would like to thank and show their deep gratitude to Dr. Abbas (Universiti Putra Malaysia) for his advice and technical support during the microstrip ring fabrication, correction, and improvement of the manuscript. The authors would also like to show appreciation to all colleagues in the field of microwave in the Physics Department of Universiti Putra Malaysia for their assistance.

AUTHOR CONTRIBUTIONS

Ahmad Fahad Ahmad and Hameda Ali Abrass contributed to the design, fabrication, data collection, and analysis. In addition, we also wrote the manuscript. Zulkifly Abbas contributed and aided in the correction and improvement of the manuscript. You Kok Yeow contributed to the check and review of the final version of the manuscript. The authors declare no conflict of interest.

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Article submitted: March 14, 2018; Peer review completed: October 11, 2018; Revised version received: October 26, 2018; Accepted: November 1, 2018; Published: January 18, 2019.
DOI: 10.15376/biores.14.1.1819-1837