Microwave Reflection Based Dielectric Spectroscopy for Moisture Content in Melele Mango Fruit (*Mangifera Indica L.*)

E.M. Cheng[1, 4], Shahriman A.B.[1], H.A. Rahim @ Samsuddin[2, 4], M.F Abdul Malek[3], N.F. Mohd Nasir[1],
N. Abdulaziz[3], M.S. Abdul Majid[1] and K.S. Basaruddin[1]
[1]*School of Mechatronic Engineering, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia.*
[2]*School of Computer and Communication Engineering, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia.*
[3]*Faculty of Engineering and Information Sciences, University of Wollongong in Dubai,*
Dubai Knowledge Village, United Arab Emirates.
[4]*Bioelectromagnetic Research Group (BioEM), Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia.*
emcheng@unimap.edu.my

***Abstract*—The Melele mango is one of the special local fruit Malaysia and it has high commercial value. However, the current methods are not efficient in determining optimum period to harvest. The optimum harvest time has close relationship with moisture content in fruit. The reflection based dielectric spectroscopic technique is conducted to measure moisture in Melele mango fruits. Dielectric and reflection measurements were conducted over a frequency range from 200 MHz to 8 GHz on clone Melele mango. Dielectric constant, loss factor and complex reflection coefficient of Melele mango with different moisture content were measured using an Agilent E8362B PNA Network Analyzer in conjunction with an Agilent 85070E High Temperature Probe over a frequency range from 200 MHz to 8 GHz. The measured reflection coefficient is presented in magnitude and phase. Dielectric constant and loss factor decreases when the moisture content in mango fruit decreases. The magnitude of the reflection coefficient descends due to increment of the dielectric constant. The results show that the measured dielectric properties and complex reflection coefficient provides the ability to predict fruit moisture content.**

***Index Terms*—Dielectric Constant; Loss Factor; Mango; Moisture Content; Reflection Coefficient.**

I. INTRODUCTION

Mango (Magnifera indica) has many popular clones that are grown in Malaysia. MA 204 (Melele) is a popular clone. Melele mango originated from Kodiang in the Kedah state of Malaysia. It has a moderate size of 11 cm × 4.5 cm with an oval shape. Its skin colour is yellowish green (Figure 1(a)). The flesh is yellowish, juicy, aromatic and fibrous. Mango fruits have been consumed widely due to their pleasant flavour and abundant vitamins A, B_6 and C. Hence, this fruit has become a lucrative industry in ASEAN countries, such as Malaysia, Thailand, Indonesia and others. The ripeness of mango fruit has always been a key indicator for consumers when making a purchase decision. Therefore, the most appropriate harvest time needs to be determined according to physico-chemical characteristics of the mango fruit at different stages of ripeness [1]. One important characteristic is moisture content as the moisture content will accumulate progressively from early to the last season. As such, moisture content in mango fruit can be indicator of fruit ripeness. The unripe mango was analyzed to have moisture content in the range of 24% [2] and vice versa.

Using standard oven drying methods [3] to measure moisture content in agricultural products requires specific time periods at specified temperatures by prescribed methods. Such methods are tedious and time-consuming, and are not suitable in agro-production. Hence, a rapid testing method such as a microwave method needs to be developed.

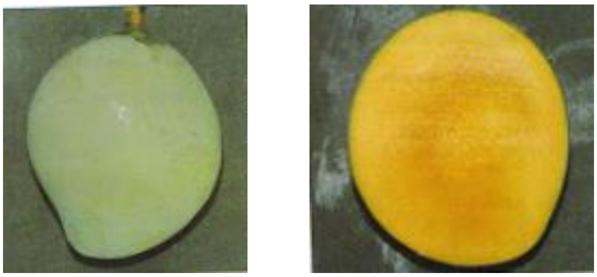
(a) (b)

Figure 1: (a) Outer skin and (b) flesh for Melele Mango

Previously, many studies looking into the electrical resistance of vegetation have shown that electrical resistance is correlated with moisture content. The high correlation between material permittivity and water content of the material has results in the usage of a microwave method to determine moisture content [4]. Hence, we propose applying this principle of sensing electrical resistance to determine moisture content in agricultural products.

The dielectric properties of agricultural products are a function of moisture content, frequency of the applied electromagnetic field, temperature, density and structure of the materials [5,6]. When an external electric field is applied in fresh agricultural products (moist material), the polar water molecules in the material takes times to build up an equilibrium polarization. If a high frequency of electric field strength is imposed, the polarization will lag behind the changing field. The dielectric properties of the material in time-dependent fields will therefore deviate from the corresponding equilibrium properties in the steady fields. Thus, the complex permittivity of material becomes a function of moisture content in a moist material, and can be applied particularly to in agricultural products.

Moisture detection has long been a topic of research [7]. A wide variety of methods have been proposed and studied, including a microwave method. Recent literature [8] explored use of a microwave method in association with moisture in agriculture. Today, such use has not been confined to electrical engineering only and has even extended to agricultural science. The dielectric properties of an agricultural product are important because the dielectric property is highly dependent on moisture content. Water molecules, H_20 contained in fruit are polar molecules that exhibit a significant dielectric property. This has been widely utilized as a parameter in agricultural engineering research. Considerable research has been done pertaining to the implementation of microwave dielectric spectroscopic techniques to agricultural products. Lee et al. and You et al. [9-11] conducted recent research on oil palm fruit to determine ripeness through moisture content level by using a microwave method. Previously, Zulkifly et al. [12-14] researched different microwave dielectric spectroscopic techniques to determine moisture content in oil palm fruit. Apart from oil palm fruit, apple fruit has also been studied dielectrically from 10 MHz to 1800 MHz [15]. In addition, a microwave method was implemented for moisture detection in other fields purpose, e.g. soil moisture detection[16], dehydration of fruit and heating[17], free water molecules in solution[18] etc. The dielectric response of fruit tissues is typically dominated by ionic conductivity and bound water relaxations at lower frequencies. Meanwhile, free water relaxation plays a vital role at a higher frequency range.

Generally, a reflection coefficient can be defined as the ratio of reflected to an incident microwave parameter. It is a function of dielectric properties and frequency. The reflection occurs due to mismatch in impedance at the interface between two media. In other words, impedance is also determined by the dielectric properties of media and frequency. This behaviour can be explained by the following equation [19]:

$$\left|\Gamma\right| = \left|\frac{1- j\omega\omega_0\varepsilon_0 C_T}{1+ j\omega\omega_0\varepsilon_0 C_T}\right| \tag{1}$$

where

$$C_T = (\varepsilon' - j\varepsilon'')C_0 + C_f \tag{2}$$

and

$$C_0 = 2.38\varepsilon_0(b-a) \tag{3}$$

where ω is angular velocity, Z_0 is characteristic impedance of a coaxial line, i.e., 50Ω, ε_0 is permittivity in free space, C_0 = capacitance of air, and C_f is capacitance of fringing field in a coaxial line. b and a is the radius of external and internal conductor of a coaxial probe, respectively (Figure 7(b)). Since C_f can be ignored in the first approximation [19], Equation (1) can be simplified as

$$\left|\Gamma\right| = \left|\frac{1- j\omega Z_0\varepsilon_0 2.38(\varepsilon' - j\varepsilon'')\varepsilon_0(b-a)}{1+ j\omega Z_0\varepsilon_0 2.38(\varepsilon' - j\varepsilon'')\varepsilon_0(b-a)}\right| \tag{4}$$

Meanwhile, phase of Γ, ϕ can be expressed as

$$\phi = \tan^{-1}\left(\frac{1- j\omega Z_0\varepsilon_0 2.38(\varepsilon' - j\varepsilon'')\varepsilon_0(b-a)}{1+ j\omega Z_0\varepsilon_0 2.38(\varepsilon' - j\varepsilon'')\varepsilon_0(b-a)}\right) \tag{5}$$

II. METHODOLOGY

Dielectric Measurement

Mango fruits with different ripeness were collected from an orchard. The fruit needed to be measured immediately to approach an *in-situ* assessment. Dielectric measurement calibration must be performed on high temperature probe in advance to remove systematic measurement errors caused by imperfections of the measurement system. The calibration is started by measuring three calibration standards: air, a short circuit, and water. Then the dielectric measurement can be conducted using 85071E Material Measurement Software attached to an Agilent E8362B PNA Network Analyzer (Figure 2). The dielectric measurement is conducted over a frequency range from 200 MHz to 8 GHz.

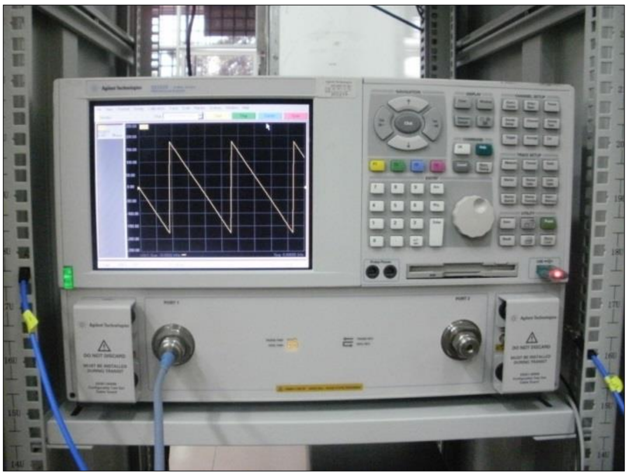

Figure 2: Agilent E8362B PNA Network Analyzer

Reflection Measurement

After dielectric measurement, further measurement of a complex reflection coefficient on the same batch of mango fruit was conducted by using an Agilent 85070E High Temperature Probe. A new procedure with a one port calibration method also needed to be conducted on a coaxial cable that connects the PNA with the probe, i.e., Short-Open-Load calibration (SOL). A one-port calibration can eliminate three systematic errors during reflection S-parameters measurements. Three known calibration standards must be measured: Short, Open, and a 50 Ω Broadband Load (Figure 3). After calibration, the reflection S-parameter (Γ) of mango fruits with different moisture content was then measured in terms of magnitude and phase (Figure 4).

Figure 3: Calibration standards of Open, Short and Broadband Load

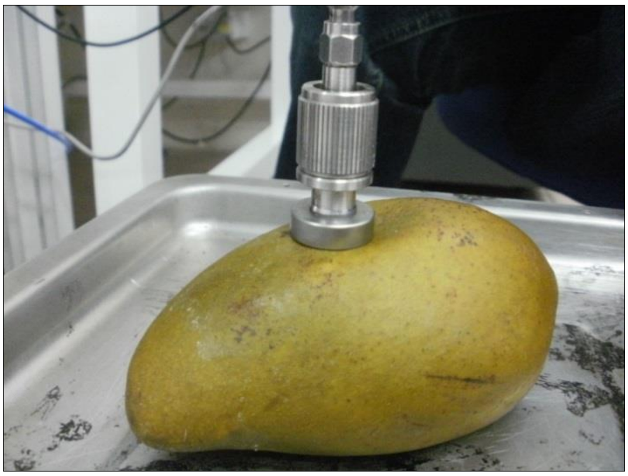

Figure 4: Dielectric and reflection measurement on mango fruit using Agilent 85070E High Temperature Probe

Both dielectric and reflection measurement were conducted using Agilent E8362B PNA Microwave Network Analyzer in conjunction with Agilent 85070E High Temperature Probe from 200 MHz to 8 GHz.

III. RESULTS AND DISCUSSIONS

A. Complex Permitivity with Moisture Content in Fruit

ε' decreases when frequency increases for moisture content exceeding 22% (Figure 5). This might be due to the presence of free water molecules in fruit. When frequency increases, free water molecules are not able to oscillate synchronously with the applied field and the orientation polarization of a water molecule lags at high frequency. This causes a decrement in the dielectric constant when frequency increases. Therefore, energy storage declines. In addition, the mass of the ionic substance, e.g., glucose, sucrose, fructose, etc., prevents free water molecules from responding to the variation of electric field at a high frequency range. In contrast, ε' increases with moisture content in fruit. It makes sense that higher moisture content implies a sufficient number of free water molecules are available in fruit. As a result, dielectric constant increases due to full polarization that can be conducted by free water molecules. Free water molecule has high mobility to synchronize with the oscillation of applied at high frequency. It further justifies this idea where water exhibits the highest dielectric constant, ranging from 70 to 80 (Figure 6).

For moisture content that is less than 22%, there are no or few free water molecules in the fruit. If the water molecules are few, they are inclined to bind with the fruit wall through a hydrogen bond to form bound water molecules. Since bound water molecules have less mobility, the resistance for a water molecule in orientation polarization is high. As a result, the variation of ε', for a less than 22% moisture content seems stagnant over frequency.

When the skin is peeled off, the variation of ε' over frequency (Figure 6) is more significant than for mango fruit with skin (Figure 5). This might be due to the direct interaction of the applied field with water molecule in the fruit without the obstruction of skin. The skin of mango fruit is fibrous and rich with carbon content that acts as mild absorbing material or reflector. Hence, the energy might be absorbed and reflected when the applied field impinges on fruit skin. Thus, less energy will be applied to the water molecules for the orientation polarization. This leads to a decrement of the dielectric constant.

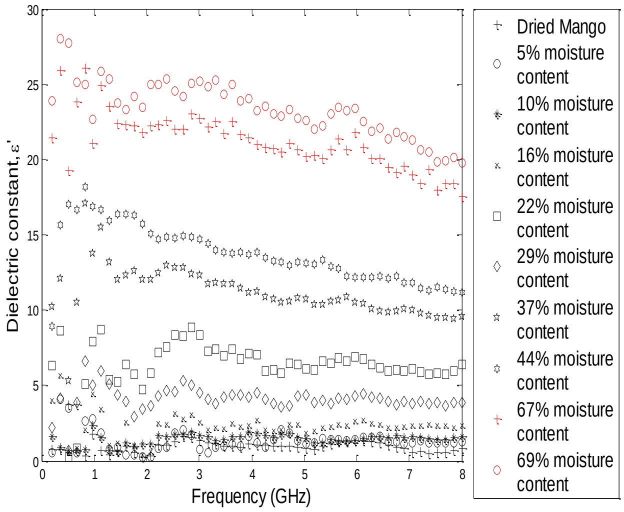

Figure 5: Variation of dielectric constant, ε' of mango fruit with skin over frequency with different moisture content percentages

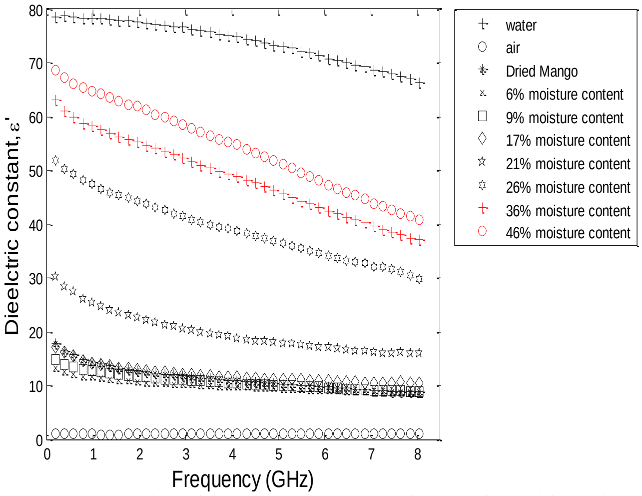

Figure 6: Variation of dielectric constant, ε' of mango fruit without skin over frequency with different moisture content percentages

The loss factor is a function of frequency for different moisture content in mango fruit (Figure 7). The parameters used were similar to the dielectric constant measurement, the frequency range used was from 200MHz to 8GHz and the moisture content was from 0% to 69%. The results were shown in Figure 7. It is clearly shown that the loss factor exhibits an increment when the moisture content exceeds 29%. This decrement of dielectric constant leads to increment of loss factor. When frequency increases, the lag orientation polarization results in an increment of frequency of friction, since the relaxation frequency of a water molecule is discrepant from the operating frequency of the applied field. The orientation polarization lags because water molecules orient asynchronously with the frequency-dependent applied field. Friction increases during orientation of water molecules when frequency increases. Heat is dissipated through friction among water molecules and the ionic substance or electrolyte in mango fruit when the orientation polarization lags. In other words, heat dissipation or heat loss determines loss factor. Hence, the increment of heat loss due to lag polarization increases the loss factor.

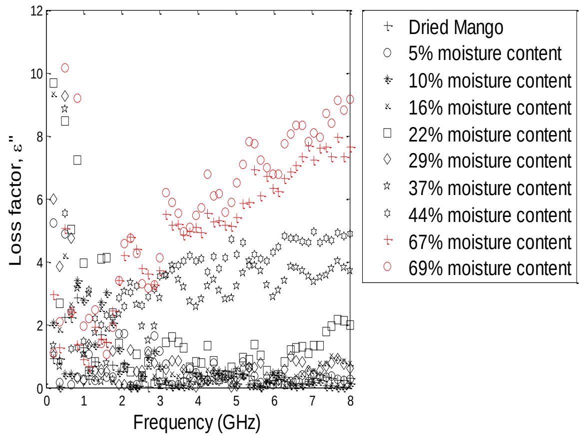

Figure 7: The variation of loss factor of mango fruit with skin over frequency for various moisture levels

Generally, the loss factor has a higher value when the skin has been peeled off and compared to mango fruit with skin (Figure 8). The removal of skin provides a better interaction between water molecules and the applied field. The orientation of water molecules occurs vigorously due to reception of more energy from the applied field after the skin obstruction has been removed. The lag orientation polarization induces severe friction and hence heightens the loss factor. In addition, loss factor increases with an increment of frequency and moisture content in fruit. The water exhibits a drastic response over frequency due to the high mobility of free water molecules in a sample of water.

IV. REFLECTION MEASUREMENT OF MANGO FRUIT WITH DIFFERENT MOISTURE CONTENT

Equation (1) to (4) show that the magnitude of the reflection coefficient varies inversely with an increment of frequency. Reflection coefficient, |Γ| decreases when frequency increases for all percentages of fruit moisture content (Figure 9).

When the coaxial line comes into contact with the fruit, a mismatch in impedance occurs due to the different dielectric properties presented by both media. The incident field from the coaxial line will be reflected when it impinges on the interface between the aperture of the coaxial line and fruit. As the impedance of the fruit is close to the characteristic impedance of the coaxial line, the mismatch impedance declined. This leads to a decrement in the reflection coefficient (Figure 9). Hence, it can be inferred that the mismatch impedance decreases progressively when frequency increases. This can be noticed from the decrement of reflection coefficient over frequency. In the meantime, it is also known that as the dielectric constant decreases, the loss factor increases with an increase in frequency. These properties also reflect the discrepancy in the impedance of the fruit from the coaxial line and cause the increment level of the mismatched impedance. It can be further inferred that the frequency response of both the dielectric constant and loss factor lead to an increment of |Γ|.

Higher moisture content leads to higher dielectric constant and loss factor (Figure 5 to Figure 8). The responses from both the dielectric constant and loss factor results in a low reflection coefficient (Figure 9 and Figure 10). The removal of skin leads to the direct exposure of flesh to the applied field. Hence, |Γ| is more sensitive to variations of frequency and moisture content because the applied field has less obstruction when compared with mango fruit with skin.

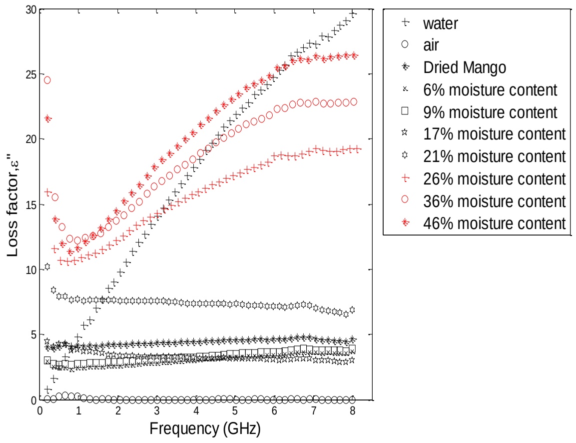

Figure 8: The variation of loss factor of mango fruit without skin over frequency for various moisture levels

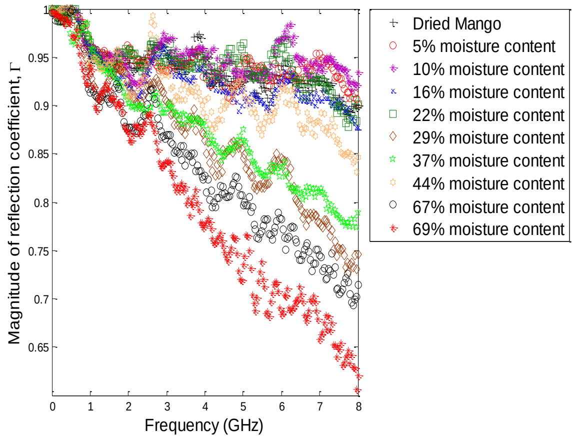

Figure 9: The effect of different moisture content in mango fruit with skin on magnitude of reflection coefficient, |Γ| for frequency range from 200 MHz to 8 GHz

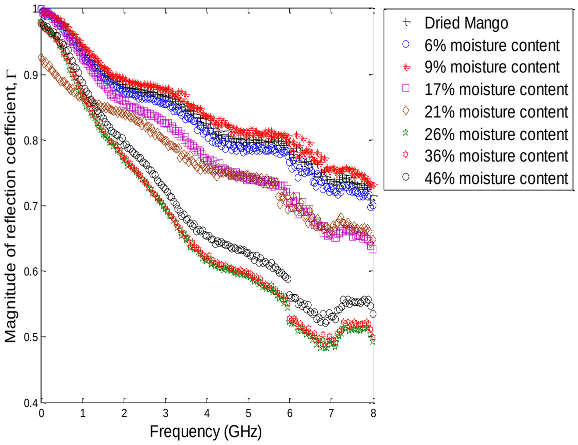

Figure 10: The effect of different moisture content in mango fruit without skin on magnitude of reflection coefficient, |Γ| for frequency range from 200 MHz to 8 GHz

However, there are similarities in |Γ| between mango fruit with skin (Figure 9) and without skin (Figure 10) where a lower |Γ| still exists within a higher range of frequency and moisture content. It is in line with the aforementioned dielectric response (Figure 5 to Figure 8).

The measured phase for mango fruit with skin (Figure 11) and without skin (Figure 12) is consistent. The negative phase increases with frequency. However, they are indistinguishable among mango fruit with different moisture content. The phase can be associated with the time delay between the incident field and reflected field. The time delay might be due to polarization and friction that occurs during the process of polarization when the applied field impinges on the interface of the two media. Measured |Γ| of mango fruit with skin is generally higher than fruit without skin. The obstruction of skin causes a severe reflection and permits less energy from the applied field for polarization. Hence, the time delay is not as severe as the fruit without skin and this is attributed to reduced obstruction of the interaction between water molecules and the applied field during polarization. This is further indicated by the low phase shift since the skin acts as a reflector to reflect the applied field. It yields a high range of |Γ| (Figure 9). When comparing effect of moisture content on phase for mango fruit with skin (Figure 11) and without skin (Figure 12), the phase of the mango fruit without skin appears within a larger phase shift when compared with mango fruit without skin.

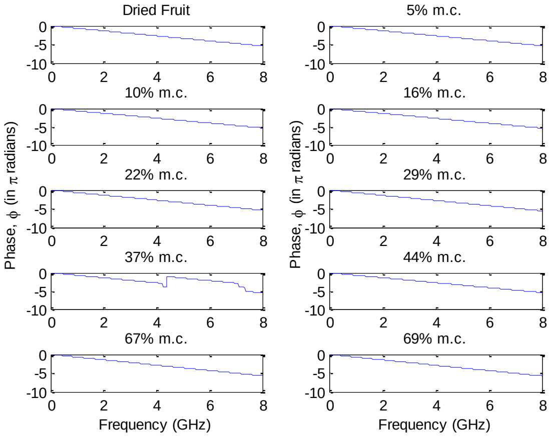

Figure 11: Effect of different moisture content in the mango fruit with skin on phase of reflection coefficient, ϕ for frequency ranging from 200 MHz to 8 GHz.

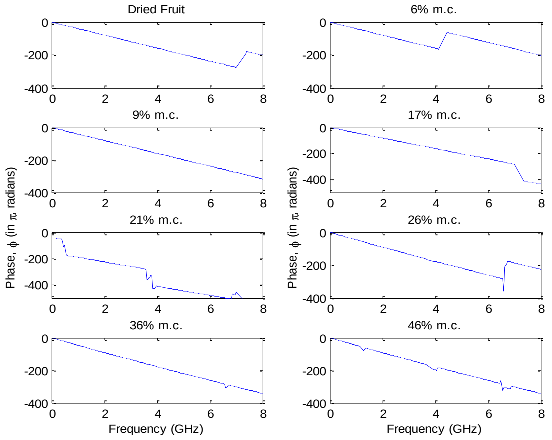

Figure 12: Effect of different moisture content in mango fruit without skin on phase of reflection coefficient, ϕ for frequency ranging from 200 MHz to 8 GHz

In addition, for both cases, phase decreases when frequency increases. This is likely due to the asynchronous relaxation frequency of molecules and operating frequency of the applied field. This phenomenon will lead to a relative static condition for the water molecules where the friction is very insignificant and negligible.

It should be noted that the measured phases (Figure 11 and Figure 12) have very insignificant variation among the different moisture contents. The water molecules are mainly responsible for dielectric behaviour. However, they are captured within the fibrous flesh. The water molecule in fruit is generally of low mobility when compared with water. The obstruction due to presence of fibre leads to an insignificant response of phase to the variation of moisture content in fruit. This is due to insufficient free water molecules being present in the fruit. Summarily, the analysis of moisture content (ripeness) of mango fruit can be categorized as listed in Table 1 in terms of dielectric constant, loss factor and magnitude of reflection coefficient, since phase is insensitive with variation of moisture content in mango fruit.

Table 1
Dielectric constant, loss factor and magnitude of reflection coefficient for ripe mango fruit

Ripeness	Ripe fruit (>24% moisture content) with skin	without skin
Dielectric constant, ε’	> 10	> 35
Loss factor, ε”	> 2	> 10
|Γ|	< 0.9	< 0.8

V. CONCLUSION

The moisture content of mango fruit varies during the ripening process. Moisture content accumulated in mango fruit from a green stage until it is ripe. Mango fruit moisture measurements were conducted using a microwave reflection measurement system. The system was comprised of an open-ended dielectric probe and vector network analyser. The dielectric mechanism was conducted when water molecules in fruit interacted with a microwave field. In general, higher fruit moisture exhibits a greater dielectric constant and loss factor. Meanwhile, this dielectric behaviour leads to decrement of the magnitude of the reflection coefficient and increment of a negative phase. Dielectric constant, loss factor and magnitude of reflection coefficient are >10, >2 and <0.9, respectively for ripe mango fruit with skin. In summary, dielectric constant, loss factor and magnitude of reflection coefficient have good agreement in moisture detection.

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