Original Research Paper

Rice Grain Moisture Determination Using Microstrip Wide-Ring and Microstrip Coupled-Line Sensors

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Abstract: Determining the Moisture Content (MC) inside rice grain is an important element for grain processesing such as harvesting, storage, quality control and transportation. A microstrip wide-ring sensor and a microstrip coupled-line sensor with low insertion loss were developed to operate at relatively low frequency to determine the MC and relative complex permittivity of rice grain. The complex permittivity for rice grain with various moisture levels was measured by the proposed sensors based on the resonance technique. Calibration equations for measurement of grain MC were obtained and validated with white rice for MC ranging from 10 to 28% wet basis. The coupled-line sensor showed better sensitivity to moisture measurement as compared to the wide-ring sensor. For a 1% change in MC, the changes of resonant frequency for the wide-ring and coupled-line sensors were 4.36 and 10.69 MHz respectively. Meanwhile, the wide-ring sensor had a higher accuracy in MC prediction than the coupled-line sensor. The average errors in moisture prediction for wide-ring and coupled-line sensors were 0.85 and 1.30% respectively.

Keywords: Moisture Content, Microstrip Coupled-Line, Microstrip Wide-Ring, Rice Grain, Dielectric Constant, Loss Factor

Introduction

Rice is a main source of nutrition for human beings especially for Asiatic populations. Moisture Content (MC) inside rice grain is a crucial parameter for grain processing such as harvesting, storage, quality control and transportation. For instance, rice grain is usually harvested between 19 and 25% MC for maximum grain yield and needs to be dried to 14% or less, depending on the season and the weather, for safe storage. Also, the ideal MC for milling is 14% in order to maximize the head rice and minimize broken grains. Thus, precise determination of the rice grain MC is important.

The conventional standard method for MC determination for grain is the oven-drying method. Although this can achieve high precision, it is time-consuming and impractical. To overcome this, indirect methods such as resistance, RF capacitance and the microwave technique have been developed. Among these, microwave technique is promising as the measurement via microwave frequency is unaffected by the ionic conductivity of water (Meyer and Schilz,

1981). There are several applications reported that used the microwave technique to sense grain MC, such as a microwave microstrip ring resonator for single wheat grain (Abegaonkar *et al*., 1999) as well as a prototype moisture meter using a microwave transceiver (Kim *et al*., 2002), multi-layer microstrip moisture sensor (Jafari *et al*., 2010) and cylindrical slot antennas for rice grain quality (You *et al*., 2011). Besides, microwave technique was also applied in MC determination for oil palm fruit (You *et al*., 2010a), soybean (Shrestha *et al*., 2014), tuber (Zainuddin *et al*., 2013), clay granule (Mextorf *et al*., 2012), latex (Ansarudin *et al*., 2012; Mohammadi *et al*., 2012) and mortar (Jusoh *et al*., 2011).

Among the microwave techniques, the microstrip ring offers many advantages; for instance, non-destructive measurement, easy sample loading and unloading compared with the waveguide resonant cavity technique (Joshi *et al*., 1997), easy fabrication into a field-portable device (Sarabandi and Li, 1997), no end effect compared to the single line resonator (Chang and Hsieh, 2004), maximum transmitted power as compared with a rejection filter (Sumesh Sofin and Aiyer, 2005)

and accurate measurement in dusty environments (Kraszewski, 1998). However, a typical microstrip ring with loose coupling will exhibit a high insertion loss of about 10 dB at the resonant frequency (Chang and Hsieh, 2004). When a signal is transmitted through the microstrip ring with high insertion loss, the transmitted signal will become very low. Because of this very low transmission signal, some of the low-cost measurement devices are unable to detect the transmitted signal. For this reason, this paper has designed a microstrip ring sensor with low insertion loss characteristic.

In microwave sensing, the relative complex permittivity is an essential parameter to determine MC of grain. It is because the interaction of microwaves with the material is governed by the complex permittivity and the dielectric constant of water is much higher than the dry material (Trabelsi *et al.*, 2009). Complex permittivity measurement techniques can be classified into transmission-reflection and resonance techniques. However, some of the existing microwave grain moisture sensor studies (Joshi *et al.*, 1997; Abegaonkar *et al.*, 1999; You *et al.*, 2011) lacked of complex permittivity characterization with respect to the MC. Limited studies that considered this characterization were based mainly on the transmission technique which has the disadvantage of operating at relatively high frequencies (9 GHz and 10.5 GHz) (Kim *et al.*, 2002; Jafari *et al.*, 2010) with the higher cost of microwave components that operate at high frequency. On the other hand, the resonance technique can accurately measure the low loss material with a low loss factor, compared to the transmission technique (Sheen, 2009). To the best of authors' knowledge, resonance-based microstrip ring sensor has not been applied to rice grain complex permittivity measurement. Moreover, this technique with high insertion loss, will suffer difficulty in resonance extraction due to broadening of the resonance curve when testing material with a high MC.

The microstrip coupled-line has been widely used in filter application. It can be developed as a bandpass filter with low insertion loss within the passband, that can be easily designed at any desired centre frequency. Besides that, it is small in size, light weight and easy to fabricate. A previous study by You *et al.* (2010b), applied the microstrip coupled-line only to rice powder MC measurement. In addition, the calibration equation for MC determination and the complex permittivity measurement were not addressed in that study. There are no studies on applying a microstrip coupled-line to rice grain MC and rice grain complex permittivity measurements.

This paper proposes microstrip wide-ring and microstrip coupled-line sensors for rice grain MC and relative complex permittivity measurements. The microstrip ring was designed to have wide ring to provide a relatively large contact area with rice grains. Also, the 50 Ω feed lines were directly coupled with the ring to realize low insertion loss at the resonant

frequency. The low insertion loss characteristic of the sensor will make the resonance measureable even for material with high MC. Bulk grain measurement in this study is distinct from the other single grain measurement (Abegaonkar *et al.*, 1999) as the grain orientation inside the resonator greatly affects the measurement sensitivity and accuracy. Moreover, the proposed coupled-line sensor is able to measure the bulk grain MC and complex permittivity rather than the powder based MC (You *et al.*, 2010b). Furthermore, a calibration equation of the coupled-line sensor is developed based on the relationship between the MC and resonant frequency. Both sensors are designed to operate at relatively low frequency (2.4-2.5 GHz) to reduce the cost. The dielectric constant and loss factor of rice grain for difference range of MC (10-28%) are also calculated using the resonance technique via both sensors in this study. Moreover, the effect of various MCs on the physical property of the rice kernels are investigated by using a Scanning Electron Microscope (SEM).

Experiment and Methods

Fabrication of Sensor

The microstrip wide-ring and the coupled-line sensors were designed using Microwave Office (MWO) software for an operation frequency range between 1 and 3 GHz, where their resonant frequencies are located at 2.49 and 2.45 GHz respectively. All sensors were fabricated on a RT/Duroid 5880 Printed Circuit Board (PCB). The dimensions of the sensors were sketched by using AutoCAD software and printed on transparent paper, then delineated on the substrate by standard photolithography and acid etching. Then, both sensors were held on an aluminum ground with two SMA connectors. Finally, the sensors were covered with an acrylic holder as illustrated in Fig. 1. Figure 2 shows the configuration and dimensions of wide-ring and coupled-line sensors. The dimensions of the sensors are tabulated in Table 1 and 2.

Table 1. Substrate specifications and dimensions of the wide-ring sensor

Substrate specifications	Dimension (mm)				
	W_r	W_f	R_i	R_o	l
$\varepsilon_{r,sub} = 2.2$ tan $\delta = 0.001$ $h = 0.381$ mm	9.03	1.14	8.92	17.96	11.09

Table 2. Substrate specifications and dimensions of the coupled-line sensor

Substrate specifications	Dimension (mm)							
	L_1	L_2	L_3	W_1	W_2	W_3	S_1	S_2
$\varepsilon_{r,sub} = 2.2$ tan $\delta = 0.001$ $h = 0.787$ mm	22.3	22.1	22.0	2.4	2.0	2.3	0.3	2.0
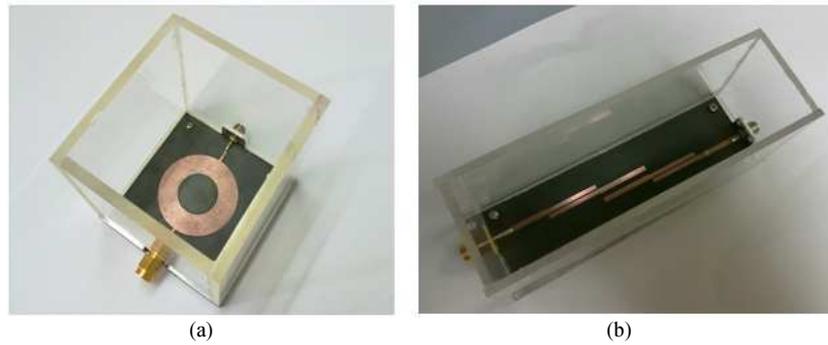
Fig. 1. The designed sensors (a) wide-ring (b) coupled-line
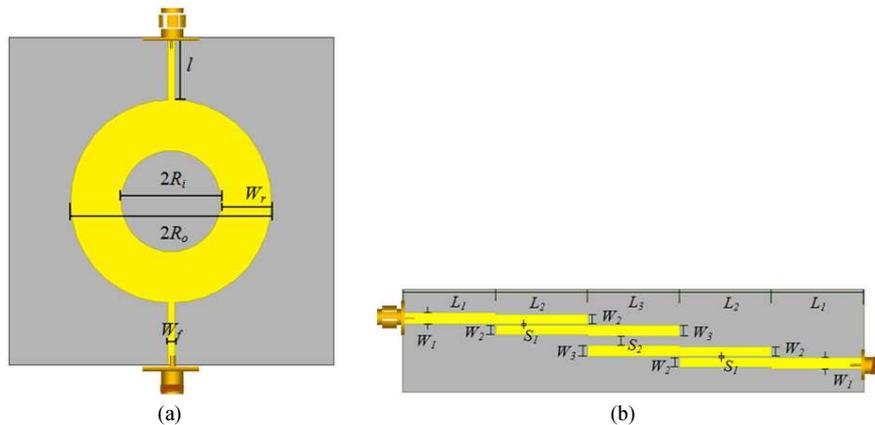
Fig. 2. Configuration and dimensions of the sensors (a) wide-ring sensor (b) coupled-line sensor

Rice Grain Sample Preparation and Measurement

Jati™ long grain white rice which is grown from the fertile soil of Kedah, the Rice Bowl of Malaysia was used as the experiment sample. The average length, width and MC (wet basis) of the grain were 7.10 mm, 2.04 mm and 14% respectively. Rice grain samples with a MC range from 10 to 28% were prepared for MC measurement. The rice grains were divided into different groups with 200 g per group. To cover the moisture range, some groups of grains were sprayed with different quantities of distilled water to achieve moisture levels ranging from 15 to 28%, while other groups of grains were dried in a forced-convection oven for some period of time to cover the MC range of 10 to 13%. The MC of each rice group was increased gradually from the lowest MC to the highest by increments of around 1%. For each group, grains were stirred and sealed in a container at 4°C for 72 h to ensure uniform water distribution within the grains. The grains were conditioned to room temperature for 10 h prior to the measurements.

A full two-port Short-Open-Load-Through (SOLT) calibration was performed at the 50 Ω coaxial cable of the Agilent E5071C network analyzer before being connected to the sensor. After the calibration, grain samples with different level of MC were placed into the sample holder of the sensor. The value of magnitude of transmission coefficient $|T|$, quality factor Q and resonant frequency f_r corresponding to different samples were obtained from the network analyzer.

After each measurement, the actual MC of the grains was obtained by the standard oven-drying method. About 10 g of each sample was dried in a forced-convection oven at 130°C for 24 h (ASABE, 2006). The MC in percent was calculated on the wet basis as:

$$MC(\%) = \frac{m_w}{m_w + m_d} \times 100 \qquad (1)$$

where, m_w and m_d are the mass of water and dry grain respectively.

Measurement of Dielectric Properties

Wide-Ring Sensor

In free space, the particular f_r for a microstrip ring depends on the effective dielectric constant ε_{eff} and the mean circumference of the ring. For material characterization, the microstrip ring was filled with rice grain that then produced a f_r shift and a broadening of the resonance curve compared to free space. The properties of

the rice grain could be characterized by measuring the shift in f_r. The f_r of the ring sensor can be approximated by:

$$f_r = \frac{nc}{2\pi r \sqrt{\varepsilon_{eff}}} \tag{2}$$

where, r is the mean radius of the ring, c is the speed of light and n is the mode number. The ε_{eff} is evaluated as:

$$\varepsilon_{eff} = \frac{\varepsilon_{r,sub} + \varepsilon_r'}{2} + \frac{\varepsilon_{r,sub} - \varepsilon_r'}{2}\left(1 + 12\frac{h}{W_r}\right)^{-0.5} \tag{3}$$

where, $\varepsilon_{r,sub}$ is the dielectric constant of the substrate, W_r is the width of the ring, h is the substrate thickness and ε_r' is the dielectric constant of the material that covers the ring sensor. When the ring sensor is fully filled with air, then ε_r' is equal to 1. In this study, the 50 Ω feed lines were coupled to the ring directly to realize low insertion loss and low radiation loss at the f_r. Consequently, the coupling effect will affect the f_r and Equation 2 was modified as follows:

$$f_r = \chi \frac{nc}{2\pi r \sqrt{\varepsilon_{eff}}} \tag{4}$$

where, χ is the corrected factor. The value of χ is obtained through the measured f_r when the ring is tested in free space. The value of χ in this study was 1.0141. When rice grain with different MC is placed on the ring sensor, f_r will be changed accordingly. The ε_r' of the rice grain can be calculated based on the measured f_r by using Equations 3 and 4.

Figure 3 shows the current distribution of the ring sensor at 2.49 GHz f_r. The current at the edge of the coupling point within the feed line and the ring exhibits the coupling effect.

The total loss of the loaded sensor (ring sensor in contact with the rice grains) can be expressed as:

$$\frac{1}{Q_l} = \frac{1}{Q_u} + \frac{1}{Q_d} + \frac{1}{Q_r} \tag{5}$$

Where:
Q_l = The loaded quality factor
Q_u = The unloaded (ring sensor in free space) quality factor
Q_d = The quality factor due to the dielectric loss
Q_r = The quality factor due to the radiation loss

In the present study, the radiation loss was negligible due to the low radiation loss design. Hence, the dielectric loss can be calculated as:

$$\frac{1}{Q_d} = \frac{1}{Q_l} - \frac{1}{Q_u} \tag{6}$$
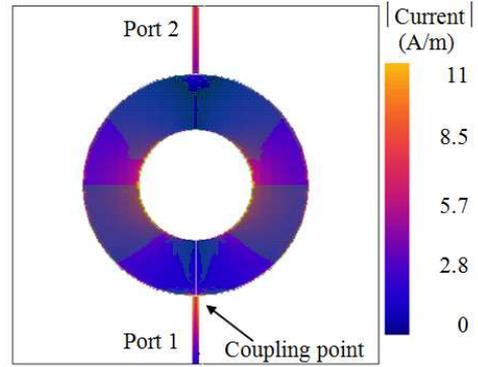
Fig. 3. Current distribution of ring sensor at 2.49 GHz f_r

The dielectric loss is related directly with the loss tangent tan δ of the loaded material as:

$$\frac{1}{Q_d} = \tan \delta = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{7}$$

The loss factor ε_r'' of the rice grain can be calculated using Equations 6 and 7.

Coupled-Line Sensor

The coupled-line sensor was designed based on a second order Butterworth bandpass filter principle. For the sake of brevity, the detailed design of the sensor physical dimensions can be referred to in the literature (Gupta *et al.*, 1996; Mongia *et al.*, 2007). The coupled-line sensor also exhibits a shift in f_r after the sensor is filled with test material. The dielectric constant ε_r' and loss factor ε_r'' of the rice grain can be determined as follows:

$$\varepsilon_r' = 1 + 2P\frac{f_u - f_l}{f_u} \tag{8}$$

$$\varepsilon_r'' = P\left(\frac{1}{Q_l} - \frac{1}{Q_u}\right) \tag{9}$$

where, P is the filling factor, f_u and f_l represent the unloaded and loaded resonant frequency respectively. The value of P is determined experimentally with a sample of known permittivity. The sample used in this study was corn oil with permittivity obtained by using Agilent 85070E Dielectric Probe and E5071C Network Analyzer. The value of P was determined as 9.0087.

Results

Effect of MC on the Physical Property of Rice Kernel

To study the effect of MCs to the physical property of rice kernels, the surface morphology of rice kernels

with various moisture levels were investigated. The measurements were performed using a Hitachi TM3000 Tabletop SEM at magnifications of 40 and 1000. Figure 4 illustrates the SEM images for rice kernels with different MCs. As the MC increased, the micro cracks on the surface of the rice kernel could be observed clearly through the microscope. The small cracks were caused by the expansion of the rice kernels.

Variation in Magnitude of Transmission Coefficient with Frequency for Various MCs

Figure 5 illustrates the magnitude of transmission coefficient $|T|$ as a function of frequency corresponding to different MCs for the wide-ring sensor and coupled-line sensor. Both sensors exhibited low insertion loss at f_r when tested in air. The minimum insertion loss for the wide-ring sensor and coupled-line sensor were close to 0.67 and 1.81 dB respectively. When the MC was increased, the f_r shifted toward lower frequencies and the maximum value of $|T|$ was decreased accordingly. The decrement of $|T|$ is due to the increment of transmission loss when the grain MC is increased.

Variation in Dielectric Properties with MC

The relationship between the dielectric constant ε_r' and loss factor ε_r'' for rice grain with various MC percentages is shown in Fig. 6.

The ε_r' and ε_r'' of rice grain as a function of MC were determined by the wide-ring sensor and coupled-line senor using Equations 3 to 7 and 8 to 9 respectively. Figure 6 shows that both ε_r' and ε_r'' are increased with the grain MC. The average ε_r' and ε_r'' for the 10 to 28% range of MC were 2.4 to 3.7 and 0.13 to 0.31 respectively. From (Nelson, 1991), the ε_r' and ε_r'' were 2.33 to 3.46 and 0.26 to 0.54 respectively for the 11 to 20.6% range of MC.

Variation in MC with Resonant Frequency

Figure 7 shows the calibration curves relating the different MCs with corresponding resonant frequency f_r for both sensors. Calibration equations based on the relationship between the MC and f_r for wide-ring and coupled-line sensor were developed with 25 and 32 sets of rice samples respectively. The calibration equations for the wide-ring sensor and coupled-line sensor are given respectively as:

$$MC = -229.28079 f_r + 566.74913 \qquad (10)$$

$$MC = -93.52012 f_l + 218.39002 \qquad (11)$$

The coefficient of determination R^2 for Equations 10 and 11 are 0.9272 and 0.8814 respectively.
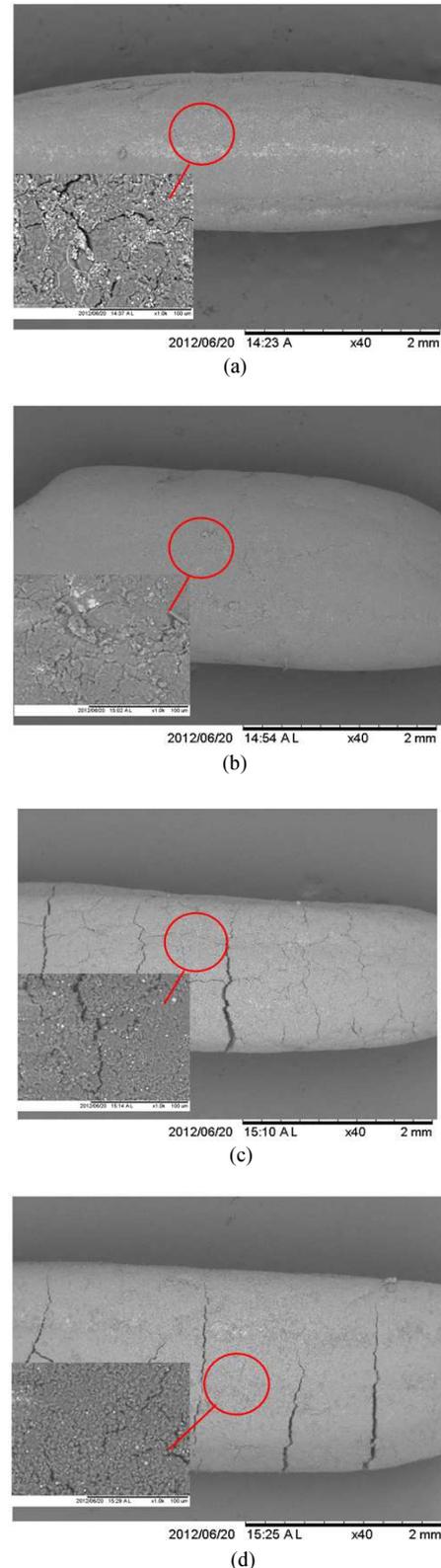
Fig. 4. SEM images for MC of rice kernels at (a) 10.45%, (b) 14.78%, (c) 20.17% and (d) 24.97% at × 40 and ×1000 magnification
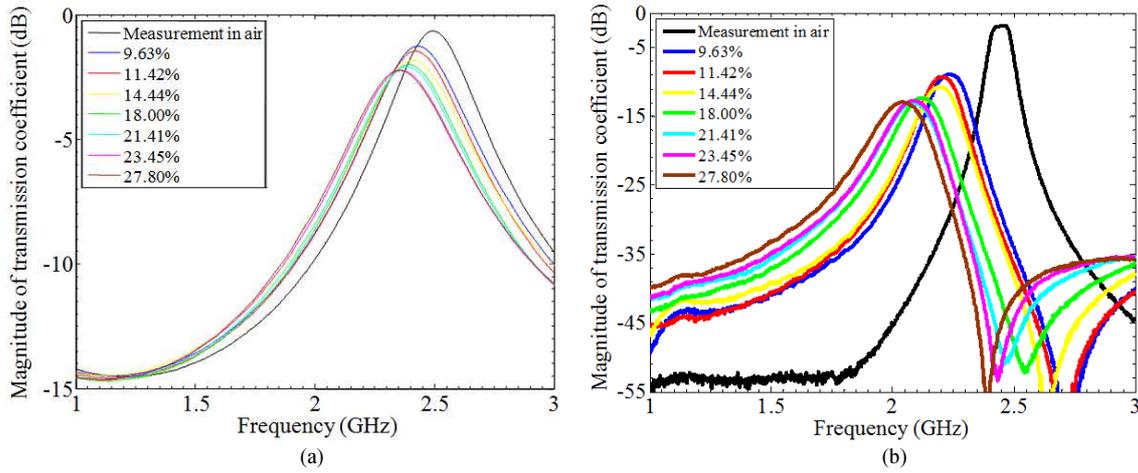
Fig. 5. Variation in magnitude of transmission coefficient with frequency corresponding to different MCs for (a) the wide-ring sensor (b) the coupled-line sensor
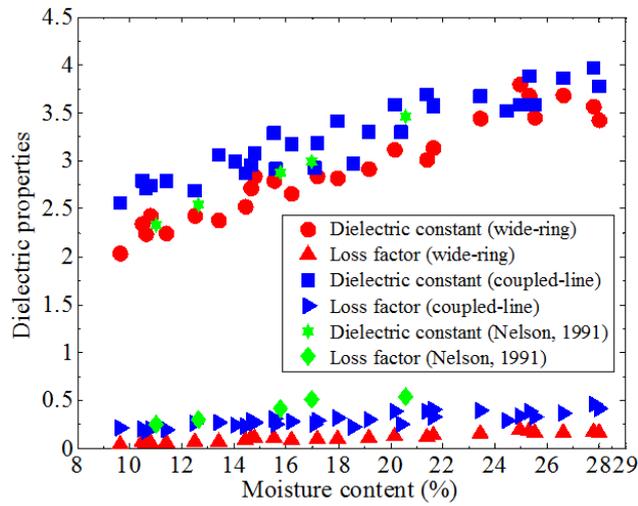
Fig. 6. Variation of dielectric properties with MC
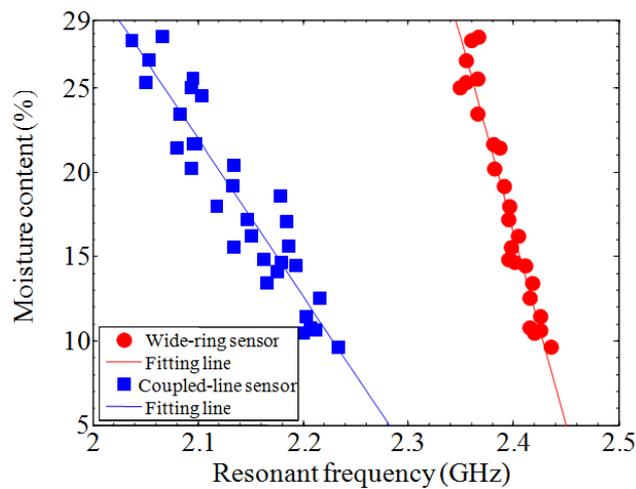
Fig. 7. Variation of MC with resonant frequency
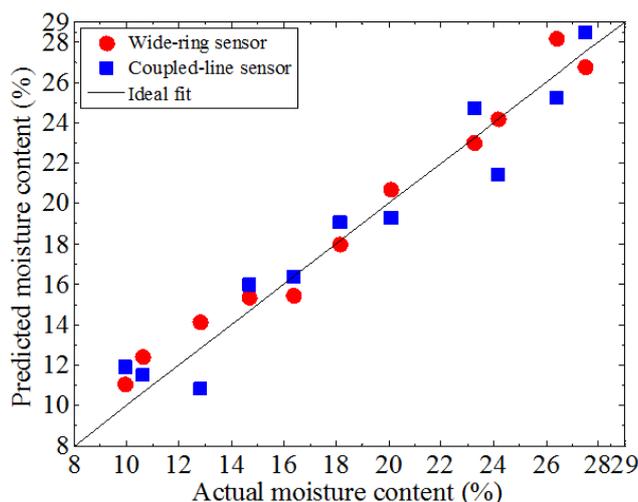
Fig. 8. Predicted MC against actual MC

The f_r of both sensors was linear with the change of MC, the $\Delta f/\Delta MC$ for wide-ring and coupled-line sensors was 4.36 MHz/MC and 10.69 MHz/MC respectively.

The Validation of the Calibration Curves

Eleven new sets of rice samples over 10 to 28% of MC were prepared to validate Equations 10 and 11. Figure 8 shows the comparison of the predicted and actual MC for both sensors.

The predicted MCs were calculated from Equations 10 and 11 while the actual MCs were obtained by the standard oven-drying method with the solid line representing the ideal fit. The predicted MCs are close to the line of ideal fit. The R^2 and average error in MC prediction for the wide-ring sensor were 0.9705 and 0.85% respectively, while for the coupled-line sensor, they were 0.9383 and 1.30% respectively.

Discussion

Considering the differences in the samples and experimental error, the rice grain complex permittivity measurement results illustrated in Fig. 6 are comparable with those of the previous study for Lebonnet long grain rough rice at 2.45 GHz (Nelson, 1991).

As shown in Fig. 7, the f_r measurement data for the coupled-line sensor was more scattered than for the wide-ring sensor. This is because the former is very sensitive to the distribution of rice kernels within the coupled-line gap. Different distribution patterns of grain within the sensor's gap affect the electromagnetic wave differently and so will give different results. Besides that, the change of resonant frequency for the coupled-line senor with a 1% change in MC is higher than that of the wide-ring sensor. Hence, the coupled-line sensor exhibits greater sensitivity in MC measurement than the wide-ring sensor.

The validation results show that both designed sensors have a high R^2 value and a low average error in MC prediction. This indicates that the predicted MCs for both sensors are in good agreement with the actual MC. The wide-ring sensor shows higher accuracy in MC prediction than the coupled-line sensor.

Conclusion

In this study, a microstrip wide-ring and a microstrip coupled-line sensor with low insertion loss have been presented as non-destructive sensors for rice grain MC and relative complex permittivity measurement. The complex permittivity of rice grain with different moisture levels has been measured by the designed sensors based on the resonance technique. Calibration equations for both sensors have been developed by using the relationship between the resonant frequency and MC. A comparative study of both sensors in MC measurement has been done. The analysis shows that the sensitivity of the coupled-line sensor is higher than the wide-ring sensor. However, the accuracy of the wide-ring sensor is higher than the coupled-line sensor. Validation tests show that the MC of rice grain can be predicted by wide-ring and coupled-line sensors with average errors of 0.85 and 1.30% respectively. The proposed sensors with their open structure that operate at relatively low frequency are suitable as low cost and non-destructive sensors for rapid rice grain moisture determination. The proposed sensors are also suitable apply for other applications such as latex and soil MC determination.

Acknowledgement

Ling Leow from Universiti Teknologi Malaysia (UTM) for their valuable suggestions and proof reading to improve the readability of this paper.

Funding Information

Author's Contributions

Hou Kit Mun: Design the research plan, conduct the experiment, data analysis and manuscript writing.

Kok Yeow You: Design the research plan, organize the study, coordinate the research process, data analysis and provide the technical guidance.

Mohamad Ngasri Dimon: Participated in study organization and research plan design.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of other authors have read and approved the manuscript and no ethical issues involved.

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