Measuring Dielectric Properties for Sensing Foreign Material in Peanuts

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***Abstract*— Free-space dielectric properties measurements at 10 GHz with four pairs of low-cost printed Yagi–Uda antennas are proposed for detecting foreign material in unshelled peanuts, including sticks, peanut shells, peanut raisins, and stones. The four-element array design of the Yagi–Uda antenna allowed better averaging over the entire sample volume and improved the measurement resolution. The antenna gain is about 9.7 dBi. The beam width of each antenna is about 18° and 38° for the E-plane and H-plane at 3 dB, respectively. The attenuation and phase shift were measured for each pair of antennas by controlling automatically the microwave switches. Measurement repeatability of the system was confirmed by using different thicknesses of polyethylene dielectric slab samples. The standard deviation was less than 0.5 dB for the attenuation and less than 5.0° for phase measurements. Sensitivity of each antenna pair for unshelled peanuts and different foreign materials, each loaded in a small volume (4.4 cm × 4.4 cm × 12.1 cm), was tested by using a partitioned sample container. It was shown that a difference in attenuation was more than 1.5 dB for different types of foreign materials and also for unshelled peanut samples with a 1% moisture content difference. Prediction of moisture content in cleaned unshelled peanut samples agreed well with the standard oven-drying method (standard error of calibration = 0.51%). The dielectric properties of foreign materials mixed with cleaned unshelled peanut samples were measured through the attenuation and phase shift. The measurement repeatability of each antenna and all four pairs of antennas is presented.**

***Index Terms*— Complex permittivity, microwave sensing, free-space measurement, foreign material, unshelled peanuts, moisture content.**

I. Introduction

DETERMINATION of foreign material in harvested peanuts is of interest in the peanut industry [1]–[4]. Since, foreign material, such as sticks, leaves, peanut shells, peanut raisins (shriveled and immature peanuts) and stones, is unwanted at the buying point, or in storage, shelling, or processing facilities, the amounts of these materials must be determined in the peanut grading process. These foreign materials occupy storage space and contribute to undesirable storage environments. Moreover, foreign materials affect the efficiency of peanut shelling and peanut processing. Generally, foreign material of less than 6% to 10% (weight basis) will be accepted for trading at the buying point. Traditionally, foreign materials have been manually extracted or removed with a foreign material extractor machine [5]. These methods are time consuming, especially for uncleaned peanuts with foreign material lower than 6%. Therefore, rapid determination of the foreign material content could improve the efficiency of foreign material extraction and benefit the grading process at the buying points. And hence, a nondestructive measurement system for foreign material determination in uncleaned unshelled peanuts would be most advantageous to the peanut industry.

Microwave measurement, which has worked well for sensing moisture content and bulk density [6], [7] and contamination detection [8], is a good candidate for nondestructive measurement of foreign material in uncleaned unshelled peanut samples. This method has the advantage of being inexpensive compared to X-ray [9] and near-infrared (NIR)-based instrumentation [10]. In addition, it has much better penetration than NIR.

Recently, the effect of foreign material on microwave peanut moisture measurement was reported [3], [4]. Because of foreign material, the predicted moisture content in uncleaned unshelled peanut samples was slightly under predicted compared to that of cleaned unshelled peanut samples. However, the type of foreign material and its mixture fractions were not reported. To investigate the prediction of foreign material content in unshelled peanut samples from measurement of their dielectric properties, it is important to understand the dielectric behaviour of foreign materials, cleaned unshelled peanuts and the foreign materials mixed with cleaned unshelled peanuts.

In this article, a microwave free-space nondestructive measurement system is proposed for foreign material content determination in unshelled peanuts containing known amounts of foreign materials. Four pairs of a printed Yagi-Uda antennas [11] were used as a low-cost sensor. The uncleaned peanut sample was placed in a polycarbonate container (Lexan) between the antennas. Four types of foreign material, sticks, peanut shells, peanut raisins and stones, were investigated. Attenuation and phase shift measurements from the four pairs of antennas were extracted by using the IQ-demodulator technique [12], [13]. Design of the microwave free-space measurement system with the four pairs of antennas, antenna testing with different thicknesses of standard materials, and

Manuscript received October 5, 2018; accepted October 31, 2018. Date of publication November 20, 2018; date of current version February 6, 2019. This work was supported in part by the Georgia Federal-State Inspection Service/Ga Institute of Technology under Grant 58-6040-7-018 and in part by the U.S. Department of Agriculture, Agricultural Research Service under contract for service with the Oak Ridge Institute for Science and Education, managed by Oak Ridge Associate University under the ARS Research Participation Program. The associate editor coordinating the review of this paper and approving it for publication was Dr. Francis P. Hindle. *(Corresponding author: Sakol Julrat.)*

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Digital Object Identifier 10.1109/JSEN.2018.2882367

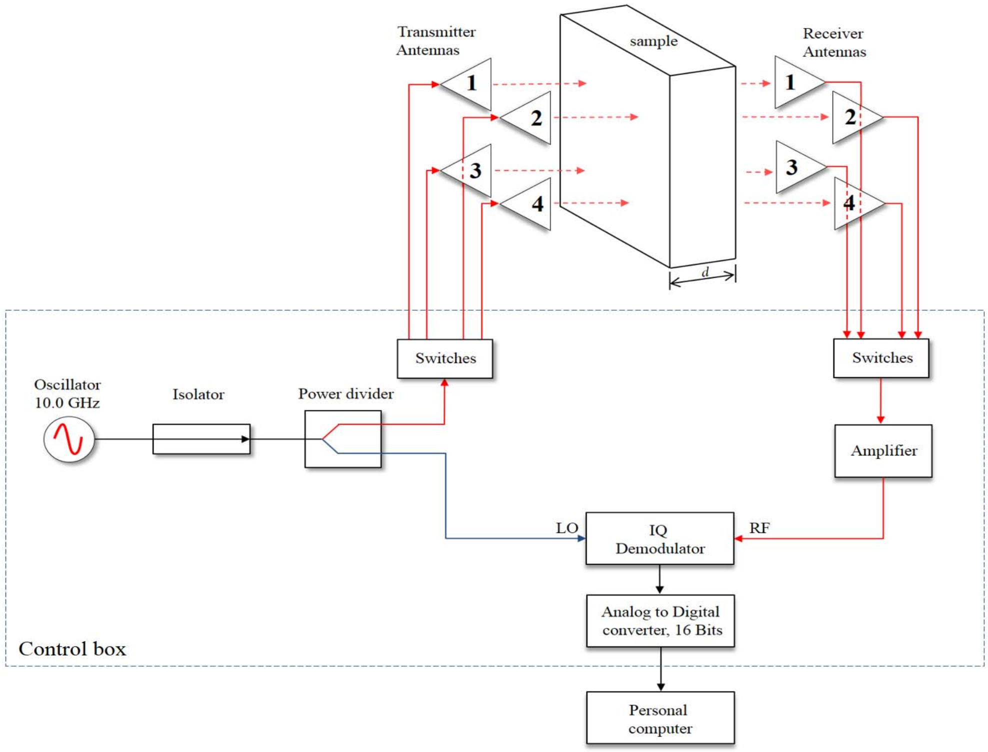


Fig. 1. Microwave measurement system for foreign material determination [13].

antenna testing with different materials in a partitioned sample container are presented in section II. In section III, results of unshelled peanut samples and cleaned unshelled peanuts mixed with small quantities of foreign materials (sticks, peanut shells, peanut raisins, or stones) are reported. Measurement repeatability for each antenna and all four pairs of antennas are presented in section V.

II. Microwave Measurement System

Free-space microwave measurement technique is well suited for the foreign material determination because it does not require contact with the peanut sample and it is a nondestructive measurement technique. The measurement frequency of 10.0 GHz was chosen because the wavelength (3 cm) is close to the average size of an unshelled peanut pod and the components at 10.0 GHz are available off-the-shelf.

A. Free-Space Microwave Measurement for Low-Loss Materials

For free-space measurements, the unshelled peanut sample was poured into the sample container, which was then placed between transmitting and receiving antennas. The dielectric properties of low-loss materials such as peanuts can be determined from measurement of attenuation and phase shift through the peanut sample as follows [6], [7], [12], [13]:

$$\varepsilon' = \left[\frac{\emptyset c}{2\pi d f}\right]^2 \tag{1}$$

$$\varepsilon'' = \frac{A}{8.686\pi d}\frac{c}{f}\sqrt{\varepsilon'} \tag{2}$$

where ε' is dielectric constant and ε'' is dielectric loss factor, $\emptyset$ is phase shift, A is attenuation, $c = 3 \times 10^8$ m/s is speed of light, d is sample thickness, and f is measurement frequency.

Figure 1. shows the block diagram of the microwave measurement system [13]. The microwave source (Miteq[1]: BCO-I-10000-4-15P) was a voltage-controlled oscillator with internal reference and operated at 10.0 GHz. An isolator with 18-dB isolation was connected to the microwave source to prevent reflected signals from reaching the source. A 3-dB power divider with output ports 1 and 2 was connected to the isolator. The microwave signal at port 1 was the reference signal and was sent to the local oscillator (LO) port of the IQ-demodulator (Polyphase microwave[1]: AD90120B). The microwave signal at port 2 was connected through switches to the transmitting antenna (four antennas, one at a time) which in turn radiates the electromagnetic energy into the material sample. The switches (Mini-Circuits[1]: MSP2T-1812+) were controlled by the measurement software which use LabVIEW® software[1]. On the other side of the sample, the receiving antennas collect the electromagnetic wave transmitted through the material sample and send the signal through the switches to the amplifier. Each pair of antennas turn on at a time with 100ms delay time. The isolation of the RF switch is about 80 dB, so, there is no mutual coupling between the antennas. The amplifier (Mini-Circuits[1]: ZX60-183A-S+) provides about 20-dB gain for the signal at the radio frequency (RF) port of the IQ-demodulator. The magnitude

[1]Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U. S. Department of Agriculture.

and phase of the microwaves transmitted through the material can be extracted from the LO and RF input signals. The RF input signal is mixed with the LO signal and provides the in- phase (I) signal. The microwave signal is mixed with the 90-degree phase-shifted LO signal and provides the quadrature (Q) signal. Therefore, the measured magnitude and phase are related to the voltages at the IQ-demodulator output as follows:

$$Magnitude = \sqrt{V_I^2 + V_Q^2} \tag{3}$$

$$Phase = \tan^{-1}\left[\frac{V_Q}{V_I}\right] \tag{4}$$

where V_I and V_Q are the voltages from the IQ-demodulator. The attenuation and phase shift are the measured magnitude and phase with the sample being tested compared to the measured magnitude and phase without the sample. The attenuation and phase shift can be expressed as follows:

$$A = Magnitude, S\ \ (dB) - Magnitude, 0\ (dB) \tag{5}$$

$$\emptyset = Phase, S\ \ (rad) - Phase, 0\ (rad) \tag{6}$$

where $Magnitude$, S and $Magnitude$, 0 are the magnitude with and without sample, respectively. $Phase$, S and $Phase$, 0 are the phase with and without sample, respectively. Attenuation is the difference between the power levels without the sample and with the sample between the transmitting and receiving antennas, which is related to the energy loss in the sample material. The phase shift characterizes the delay in propagation caused by the slowing of the speed of propagation of the wave in the sample material, which is related to the energy storage in the material.

B. Yagi-Uda Antenna

The Yagi-Uda printed antenna structure [11], [14] was chosen because of its low cross-section profile and simple structure compared to a microstrip patch antenna [15]. This antenna structure is very flexible for improving the measurement resolution desired in this application. For this purpose, a measurement technique with four pairs of the Yagi-Uda antennas was selected. A sample container (made of low-loss martial) similar to the one described previously [12], [13] with cross-section dimensions of 22 cm by 22 cm was equally divided into four areas (each cross-sectional area = 4.4 cm × 4.4 cm) corresponding to the four antenna pairs. This particular configuration of the sample container constitutes the design constraint for the antenna parameters, including beam width, gain and size of the antenna.

The Yagi-Uda printed antenna structure [11] was designed for 10.0 GHz. The four-element array design of the Yagi-Uda antenna allowed the control of the beam width of the antenna within the cross-sectional area of 4.4 cm × 4.4 cm. Electromagnetic simulation software (COMSOL multiphysics®) was used to design and simulate the antenna. The antenna was designed on FR4 substrate with feed line structure consisting of 50 Ω, 70 Ω and 100 Ω lines. Seventeen elements of the director were optimized to improve antenna gain as illustrated in Fig. 2. The antenna dimensions are listed in Table I.

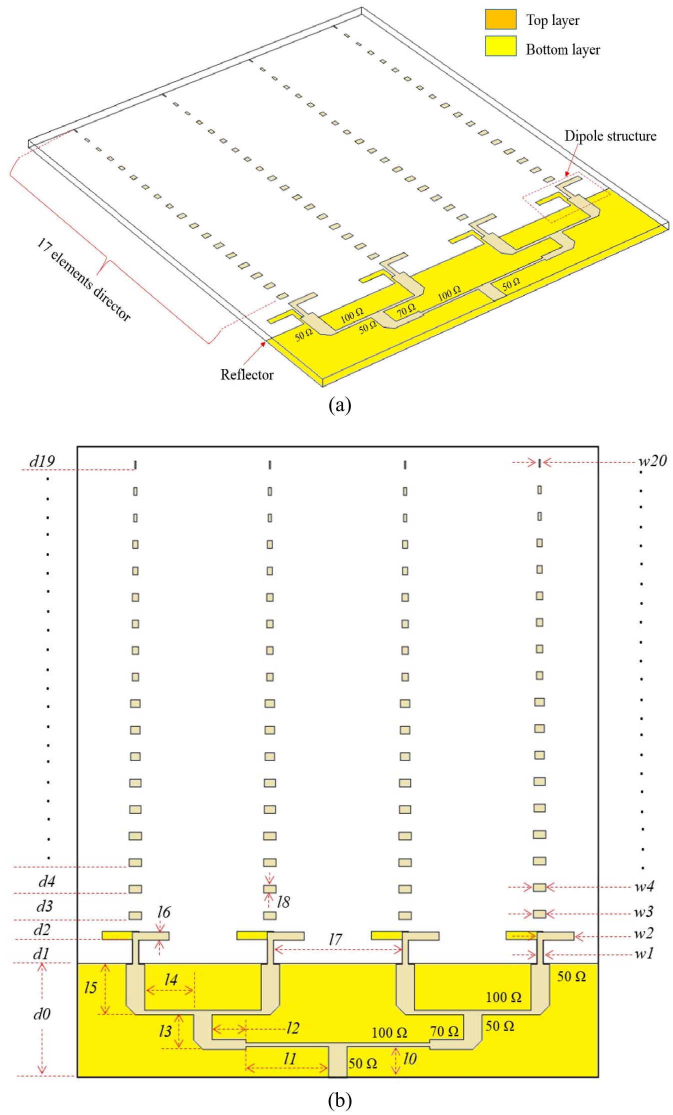


Fig. 2. Four-element array Yagi-Uda antenna.

The simulated and measured return loss of the antennas are illustrated in Fig. 3. Measurement of |S11| were performed with an Automatic network analyzer (Agilent ENA Series E5071C). For all antennas, the magnitude of S11 shows good matching at 10.0 GHz with |S11| lower than −15dB for both simulation and measurements. From Fig. 3, the trend of |S11| is slightly shifted to the lower frequency (9.8 GHz) because of the variation in fabrication processes.

The realized gain of the fabricated antenna was measured with a far-field setup (at distance of 80 cm) by using a standard-gain horn antenna (WR-75, Pasternack, PE9855-10). The simulated and measured co-polarization realized-gain radiation patterns for E-plane and H-plane at 10.0 GHz are shown in Fig. 4. For all antennas, the average measured beam width is about 17 degrees and 28 degrees for E-plane and H-plane at 3dB, respectively. The average maximum endfire realized gain of the fabricated antennas is about 9.7 dBi which is lower than the simulation (11.2 dBi). The beam width is dramatically decreased more than 50% for both

TABLE I
ANTENNA DIMENSIONS

Parameters	mm	Parameters	mm
d0	17.96	*w1*	1.00
d1	3.84	*w2*	6.00
d2	1.98	*w3 to w8*	2.00
d3 to d19	4.20	*W9 to w11*	1.50
l0	4.90	*w12 to w15*	1.00
l1	13.50	*w16 to w17*	0.80
l2	5.50	*w18 to w19*	0.50
l3	5.50	*w20*	0.20
l4	8.00	*Width of line 50Ω*	3.00
l5	8.00	*Width of line 70Ω*	1.54
l6	1.26	*Width of line 100Ω*	0.69
l7	21.0	*Width of board*	85.00
l8	2.00	*Length of board*	100.00

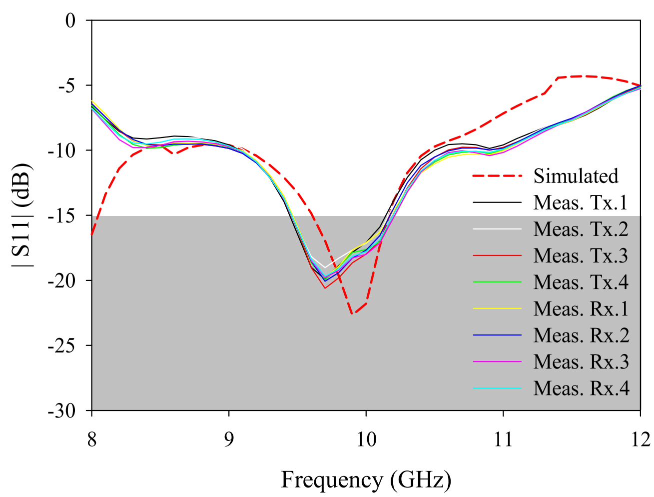


Fig. 3. Simulated and measured S-parameter of the printed Yagi-Uda antenna.

E-plane and H-plane compared to the Yagi antenna described elsewhere [11]. The design parameters of the antenna met the design goal. The fabricated antenna can sense a small cross-sectional area such as the 4.4 cm × 4.4 cm sections of the partitioned sample container.

C. System Integration

All microwave components shown in Fig. 1 and electrical components such as power supplies and switching circuit controller were assembled in the control box. The four pairs of antennas were mounted on the top of the control box with mounting stands fabricated with nGen co-polyester 3D printing filament material [16]. Electromagnetic wave absorber sheet material was placed on the control box under the antennas to reduce unwanted reflections. Flexible microwave cables were inserted through a hole in the control box to connect the antennas to the microwave circuit. The open prototype at 10 GHz with four pairs of Yagi-Uda antenna is shown in Fig. 5.

D. Dielectric Slab Testing

Polyethylene with carbon (TIVAR ESD) dielectric slabs ($\varepsilon = 2.50 - j0.25$) of three different thicknesses, 5.2 cm,

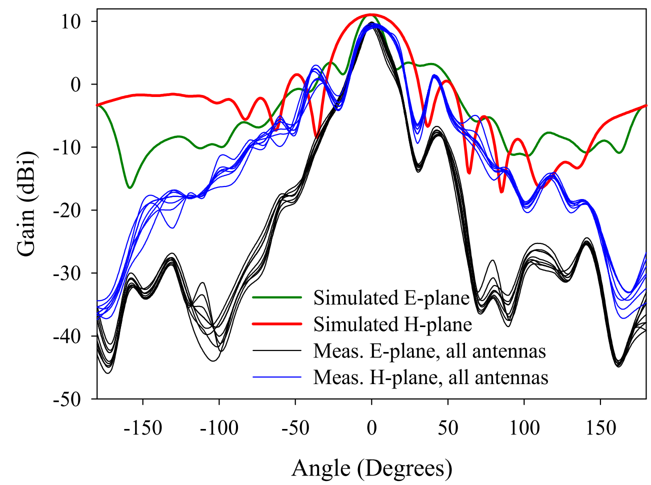


Fig. 4. Simulated and measured co-polarization realized-gain pattern of the printed Yagi-Uda antenna.

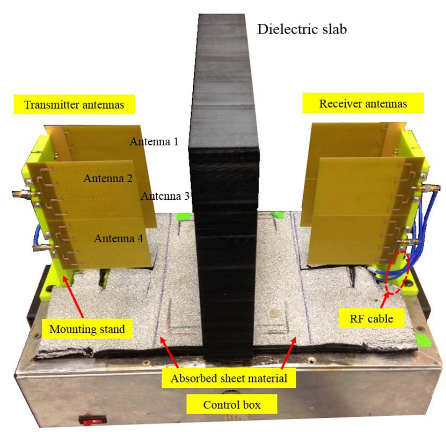


Fig. 5. The four pairs of Yagi-Uda antennas prototype at 10-GHz with dielectric slab between the antennas.

8.1 cm and 10.1 cm, were used for testing the system. The cross-section of the dielectric slabs was 31 cm × 31 cm. The measurement setup is illustrated in Fig. 5. It should be noted that antennas 1 and 3 are placed on the opposite side compared to antennas 2 and 4, to avoid for the microstrip feeding line to be facing the mounting stand. However, the linear polarization of each antenna pair is in the same direction. Therefore, the electromagnetics wave interaction with the sample under test is the same for all pairs of antenna. The proposed system was calibrated with air at room temperature (23 °C), and then the permittivities of the dielectric slabs were measured by placing them at the midpoint between the antennas (Fig. 5). Three measurements were taken on each slab, with rotation of the dielectric slab about its axis parallel to the direction of wave propagation. Mean values for measurements are listed in Table II. The standard deviation for these measurements was less than 0.5 dB and 3.5 degrees for the attenuation and phase measurements, respectively. These errors are comparable to those given in the data sheet for the IQ-demodulator, which are about ±0.5 dB and ±4.0 degrees for the amplitude imbalance and quadrature phase error, respectively. Therefore, measurement results for each antenna agreed closely and compared

TABLE II
DIELECTRIC SLAB MEASUREMENTS

	Thickness 5.2 cm		Thickness 8.1 cm		Thickness 10.1 cm	
	A (dB)	Ø (Deg.)	*A* (dB)	Ø (Deg.)	*A* (dB)	Ø (Deg.)
Horn-lens	6.20	-356.08	13.69	-568.64	16.52	-734.23
Ant.1	6.39	-367.16	11.52	-508.16	13.54	-703.55
Ant.2	6.63	-369.02	11.43	-504.09	13.81	-711.62
Ant.3	6.70	-371.56	11.40	-505.68	13.04	-705.67
Ant.4	6.92	-365.59	11.26	-503.03	13.56	-706.50

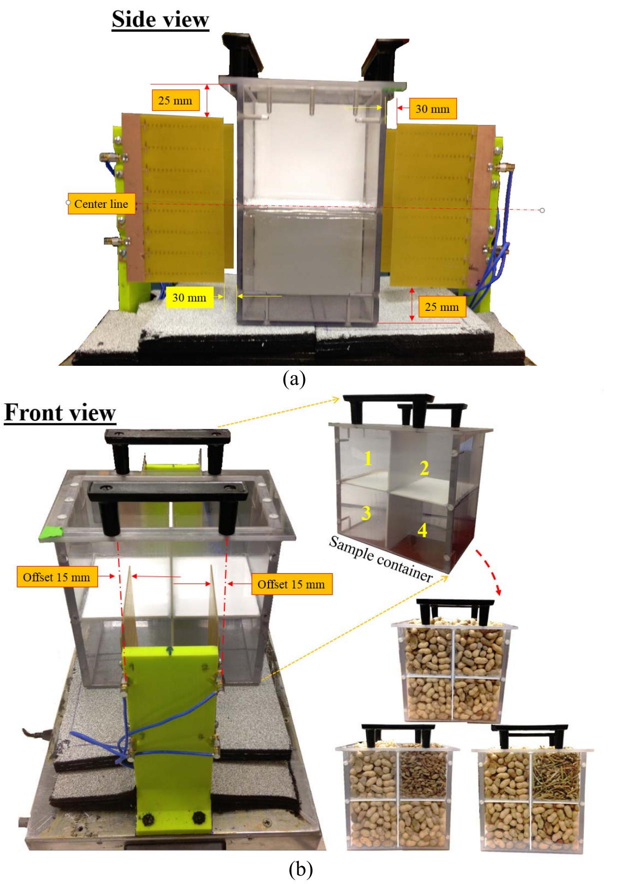


Fig. 6. Measurement setup with partitioned sample container, (a) side view and (b) front view.

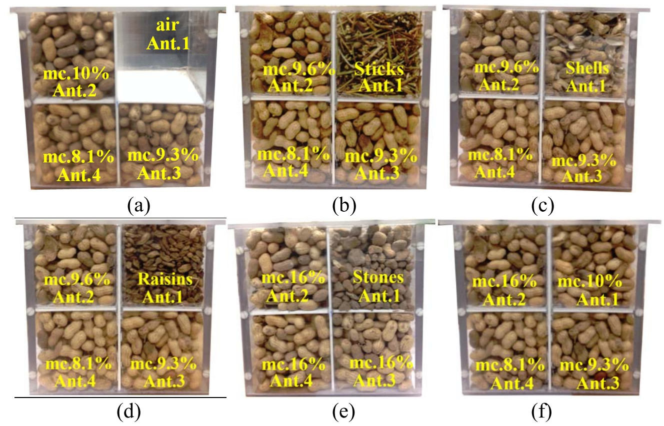


Fig. 7. Partitioned measurement setup, (a) air, (b) sticks, (c) shells, (d) raisins, (e) stones and (f) unshelled peanuts at different moisture contents.

well with measurements obtained with the horn-lens antennas and automatic network analyzer system [17].

The difference between results with the two systems may be due to detector nonlinearity. However, since the performance of each pair of Yagi-Uda antennas agreed closely, it implies that they can be used for measuring the dielectric properties with a single average value for both attenuation and phase.

E. Sensitivity Testing

The sensitivity of each pair of antennas was tested through the partitioned sample container. The sample container made of polycarbonate (Lexan), was partitioned into four sections with acrylic sheet for the walls and sealed with hot glue. The open prototype setup with partitioned container is shown in Fig. 6. In the side view of Fig. 6 (a), the sample container was placed between the transmitting and receiving antennas, with one wavelength (30 mm) [12], [13] horizontal spacing between the antennas and the edge of the sample container. In the vertical direction, the sample container was placed symmetrically between antennas 2 and 4 and antennas 1 and 3. The upper edge of antennas 1 and 2 is 25 mm from the top edge of the container while the lower edge of antennas 3 and 4 is 25 mm from the bottom edge of the container. In Fig. 6 (b), the antenna position was optimized by offsetting it 15 mm from the centre position of each partitioned container because of the high radiation beam in the H-plane. This reduces unwanted radiation outside the container and fully covers the area between the antennas. The proposed system was calibrated with empty partitioned container (air) to eliminate the unwanted wave scattering and mismatch impedances. Then, the four partitioned sections were filled with different materials such as air, peanut raisins, peanut shells, sticks, stones and cleaned unshelled peanuts. Fig. 7 shows the partitioned sample container setup for measurements with unshelled peanuts in three of the sections and air (a), sticks (b), peanut shells (c), peanut raisins (d), and stones (e), in the other section. Fig. 7 (f) shows the measurement setup for clean unshelled peanut samples at four different moisture contents. The measured attenuation was used for evaluating the performance of the antennas. The measurement results at room temperature (23 °C) are listed in Table III.

From Table III, the measured attenuation for each sample in the partitioned container is related to its physical properties. The attenuation of air is very low (2.6 dB) while that of stones is very high (42 dB). The attenuation of shells (5.1 dB), sticks (6.8 dB) and raisins (11.3 dB) are lower than that for the unshelled peanuts sample (∼12.6 dB) at 8.1% moisture content. The attenuation of peanut samples increases significantly with moisture content. Moreover, excellent sensitivity of the proposed system was observed from the measured attenuation for the peanut samples (8.1%, 9.3% and 10.0%

TABLE III
PARTITIONED MEASUREMENTS

Partitioned setup	Attenuation (dB)			
	Ant.1	Ant.2	Ant.3	Ant.4
(a) Air with peanuts	***2.6***	18.2	15.4	12.3
(b) Sticks with peanuts	***6.8***	16.8	14.7	12.9
(c) Shells with peanuts	***5.1***	17.4	14.5	12.9
(d) Raisins with peanuts	***11.3***	17.5	15.0	12.8
(e) Stones with peanuts	***42.0***	31.3	30.2	29.7
(f) Peanuts, different moisture contents	18.2	31.6	15.3	13.0

Fig. 8. Prototype with metal cover.

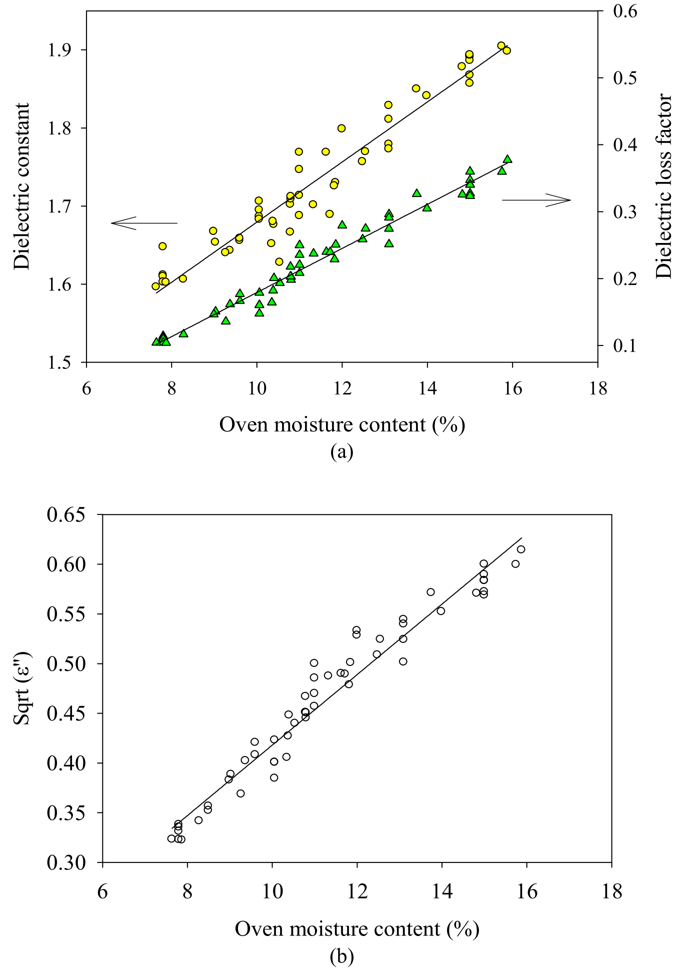


Fig. 9. Measured dielectric properties of cleaned unshelled peanut at room temperature (23 °C), (a) dielectric properties and (b) square root of dielectric loss factor.

moisture content). This implies that the main radiation beam of the antenna is focused in a specific area of the partitioned sample container, which allows for moisture content sensing in a small volume and in-turn increases the measurement resolution.

III. Dielectric Properties Measurements

Fig. 8 shows the microwave measurement system with the top cover (polyvinylchloride and metal) [12], [13]. Microwave absorbing material was used to protect from unwanted reflections caused by the top cover. The cover improves during loading and unloading samples. The sample container was not partitioned for these measurements. The partitioned sample container was used just for proving the beam width of the antennas and sensitivity to different types of material. The non-partitioned sample container is more flexible and practical for sample loading. Three measurements on the same sample (reloading between measurements) were performed for each sample and used for evaluating the measurement repeatability of the proposed system. The average values of magnitude and phase from the four antennas were used to calculate the dielectric properties by using equations (1) and (2).

A. Cleaned Unshelled Peanuts

Several cleaned unshelled peanut samples at various moisture contents were prepared at room temperature (23 °C). Each cleaned unshelled peanut sample was loaded into the sample container by carefully spreading the unshelled peanuts layer by layer without applying any force to pack the sample. Measured dielectric properties of cleaned peanut samples are shown in Fig. 9. The dielectric properties of cleaned unshelled peanuts increased with moisture content which was determined by the standard oven-drying method [18]. The dielectric loss factor has a better linear relationship with moisture content than does the dielectric constant. Furthermore, a high correlation between the square root of the dielectric loss factor [19] and the moisture content can be observed. Therefore, moisture content can be determined from the following relationship:

$$\sqrt{\varepsilon''} = 0.0355MC + 0.0634, \quad R^2 = 0.954 \tag{7}$$

The standard error of calibration (*SEC*) can be used for evaluating the performance of equation (7). The calculated *SEC* of the proposed system for moisture content prediction was 0.51%. This implies good measurement repeatability for each antenna and for all four pairs of antennas when measuring the clean unshelled peanut samples.

B. Cleaned Peanuts Mixed With Foreign Materials

The prototype shown in Fig. 8 was used for measurements on unshelled peanut samples with added foreign material mixed in. Foreign materials including sticks, peanut shells,

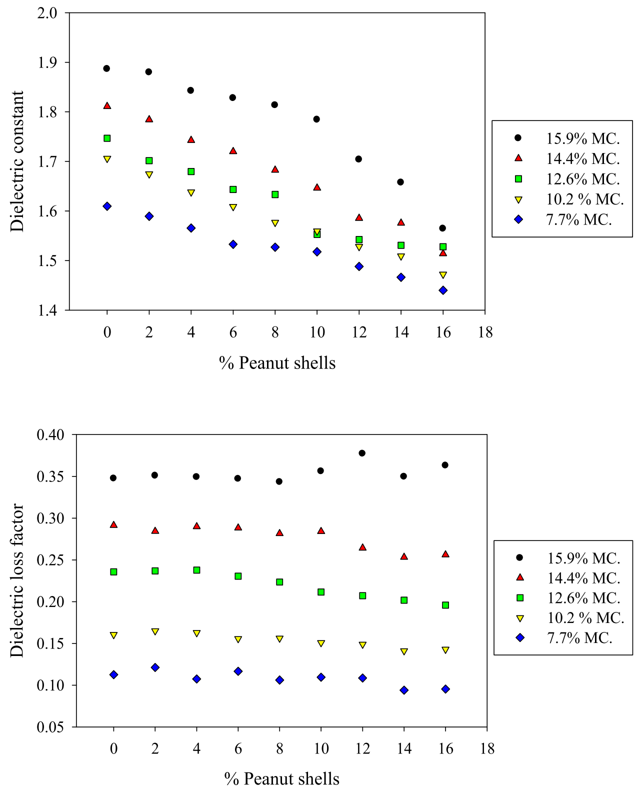


Fig. 10. Measured dielectric properties of unshelled peanuts with peanut shells foreign material at room temperature (23 °C).

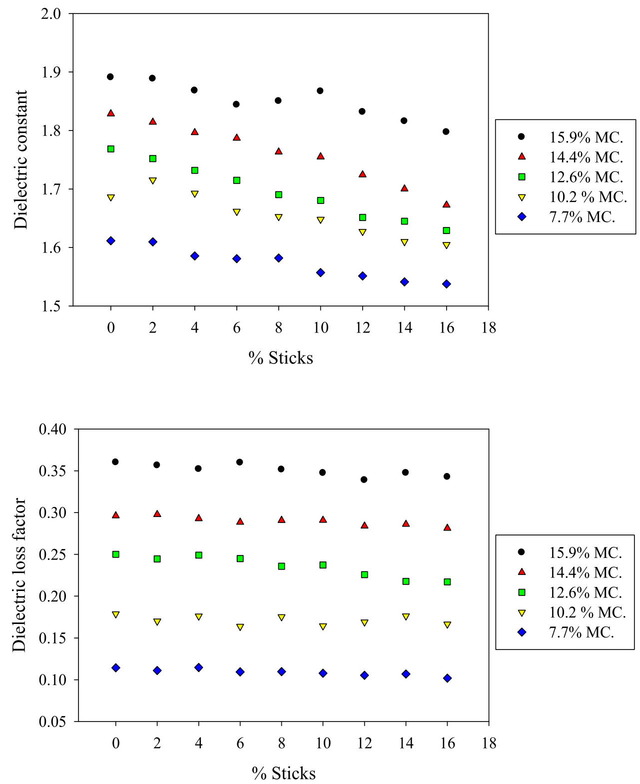


Fig. 11. Measured dielectric properties of unshelled peanuts with sticks foreign material at room temperature (23 °C).

peanut raisins and stones were added individually to cleaned unshelled peanuts. Several cleaned unshelled peanut samples were prepared at various moisture contents, and known quantities of a single type of foreign material were mixed with them. The percentage of foreign material for each peanut sample was determined on a weight basis. Foreign material content ranged from 2% to 16% with 2% increasement. Each foreign material was thoroughly mixed with the cleaned unshelled peanuts and then loaded into the sample container by carefully spreading them layer by layer to avoid having empty pockets near the corners and edges without applying any pressure. Dielectric properties measurements were performed at room temperature (23 °C).

The dielectric properties decreased with increasing peanut shells foreign material for moisture contents ranging from 7.7% to 15.9%. Moreover, the dielectric constant is more noticeably influenced by the peanut shells foreign material than is the dielectric loss factor, because the permittivity of peanut shells ($\varepsilon = 1.177 - j0.045$) is much lower than that of the cleaned unshelled peanuts.

Fig. 11 shows the dielectric properties of unshelled peanuts mixed with sticks foreign material at various moisture contents. The measured dielectric properties decreased with increasing percentage of sticks foreign material. The dielectric constant is more influenced by the foreign material than is the dielectric loss factor, because the permittivity of sticks ($\varepsilon = 1.305 - j0.067$) is lower than that of the unshelled peanuts.

The measured dielectric properties of peanuts mixed with peanut-raisins foreign material varied less with foreign material content. This is because the permittivity of peanut-raisins ($\varepsilon = 1.480 - j0.105$) is very close to that of the peanuts with 7.7% moisture content. As illustrated in Fig. 12, the dielectric properties of peanuts with peanut-raisins foreign material decreased slightly with increasing foreign-material content and showing more influence of the foreign material on unshelled peanut at higher moisture contents.

Fig. 13 shows the dielectric properties of unshelled peanuts mixed with stones foreign material at various moisture contents. The dielectric properties increased with increasing foreign material for all moisture contents, because the permittivity of stones ($\varepsilon = 3.376 - j0.865$) is higher than that of the peanuts. Moreover, it can be observed that the dielectric properties are more influenced by the foreign material in samples with lower moisture content than they are in samples of higher moisture content.

The measurement results in Figs. 10 to 13 show that the dielectric properties are influenced by the foreign material. The degree of influence depends on the dielectric properties of the foreign materials and the moisture content of the unshelled peanuts. The sensitivity of the measurements for all four types of foreign material indicate that the proposed system can be used for measuring the dielectric properties of the peanuts mixed with foreign material. Therefore, foreign material content can be determined nondestructively from measurement of the dielectric properties at a single microwave frequency. This allows the system to be simple and cost effective.

IV. Measurement Repeatability

To evaluate the performance of the proposed system for foreign material measurements, the measurement repeatability

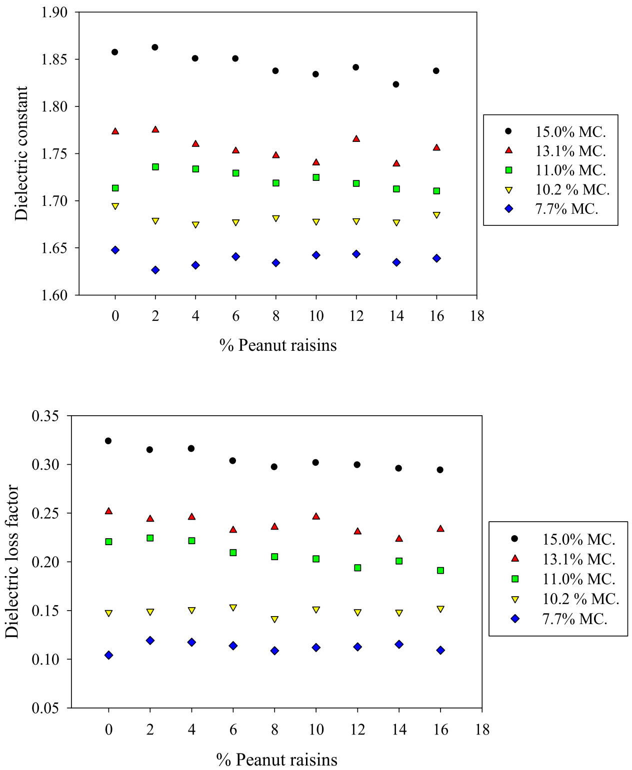


Fig. 12. Measured dielectric properties of unshelled peanuts with peanut-raisins foreign material at room temperature (23 °C).

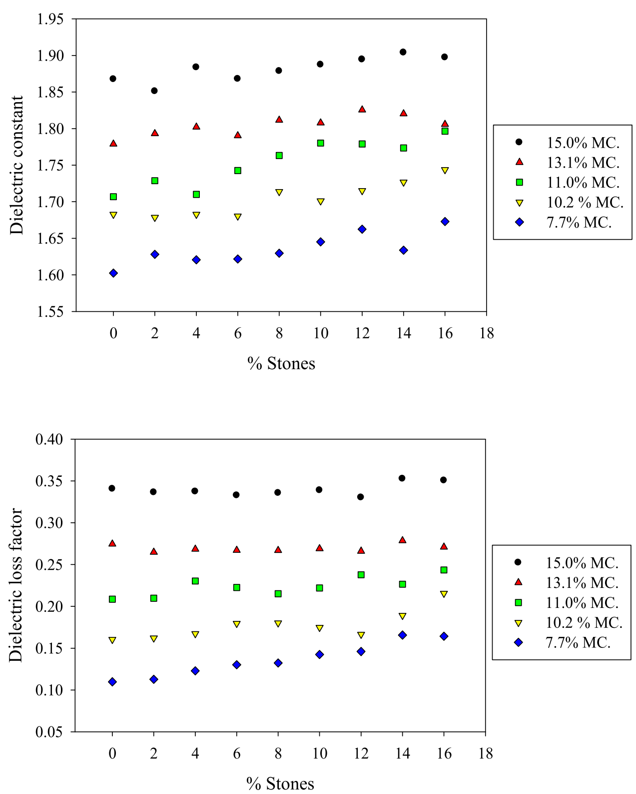


Fig. 13. Measured dielectric properties of unshelled peanuts with stones foreign material at room temperature (23 °C).

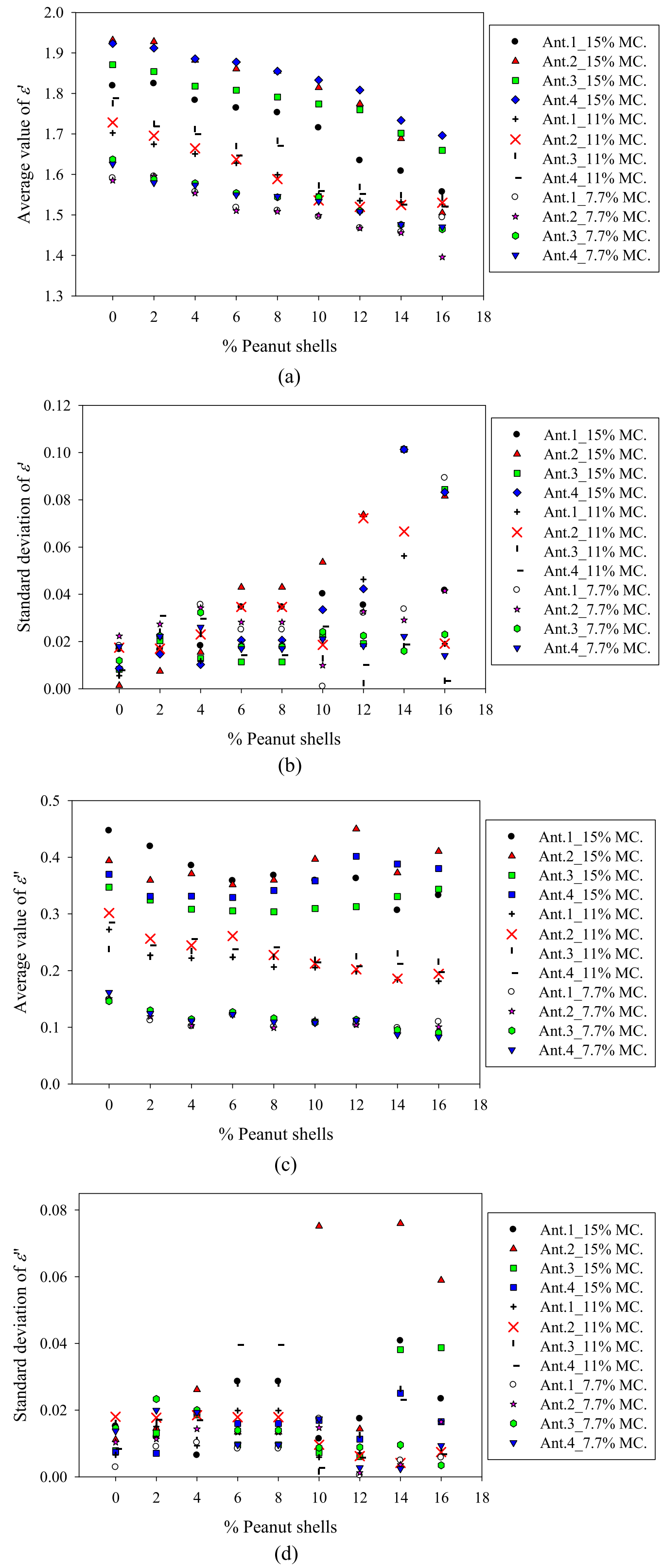


Fig. 14. Repeatability measurements for unshelled peanuts with peanut shells foreign material at room temperature (23 °C), (a) average value of ε', (a) standard deviation of ε', (c) average value of ε'' and (d) standard deviation of ε''.

and reproducibility were considered. The mixture of foreign material and unshelled peanuts is a nonhomogeneous material. In addition, the orientations of unshelled peanuts and the foreign materials are completely random in the sample container. These factors affect the dielectric properties measurements. For example, different readings may be obtained

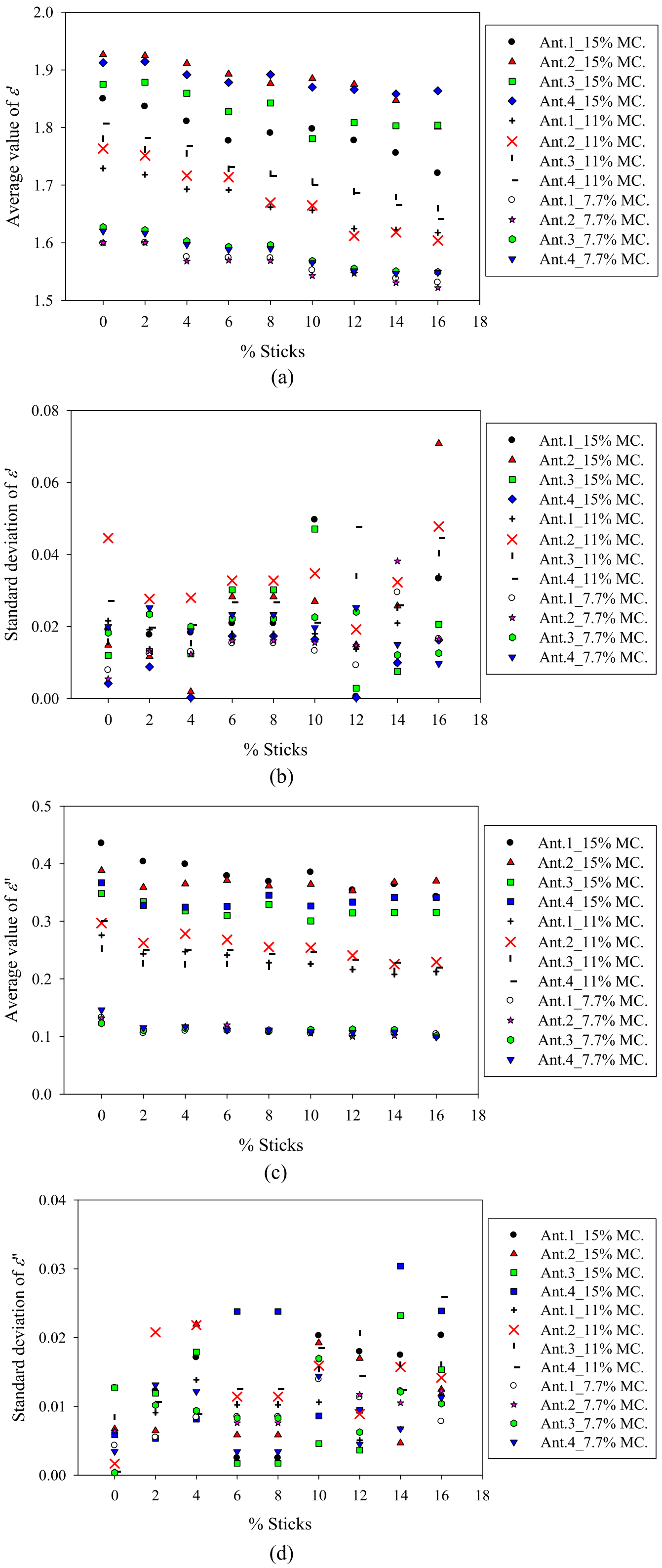


Fig. 15. Repeatability measurements for unshelled peanut with sticks foreign material at room temperature (23 °C), (a) average value of ε', (a) standard deviation of ε', (c) average value of ε'' and (d) standard deviation of ε''.

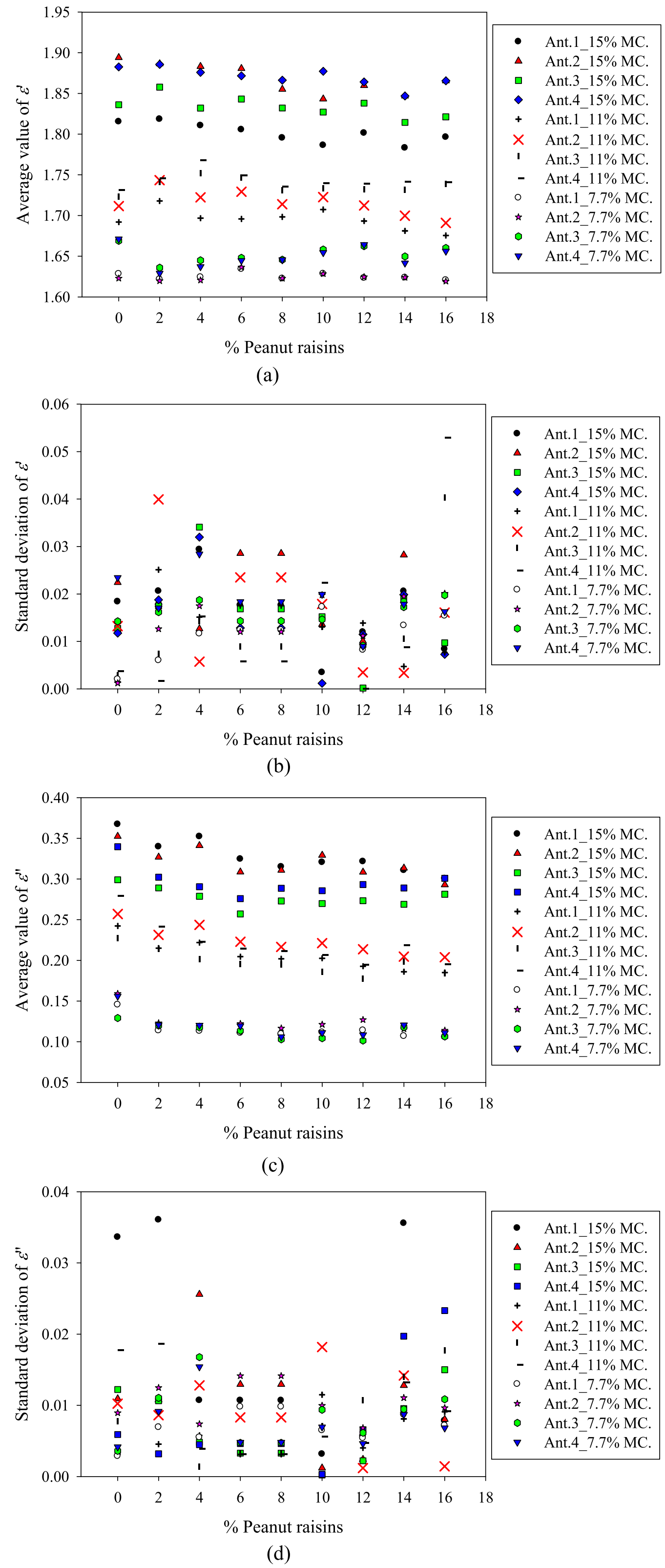
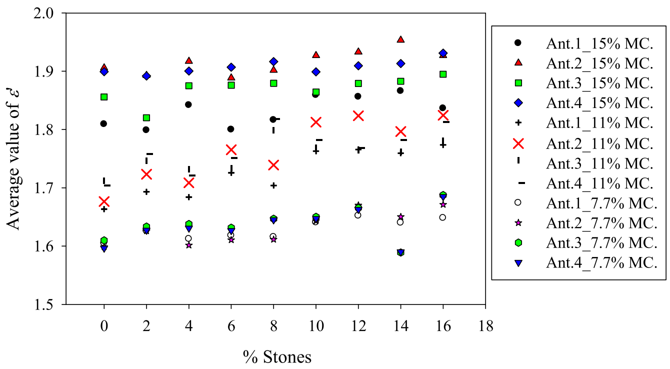
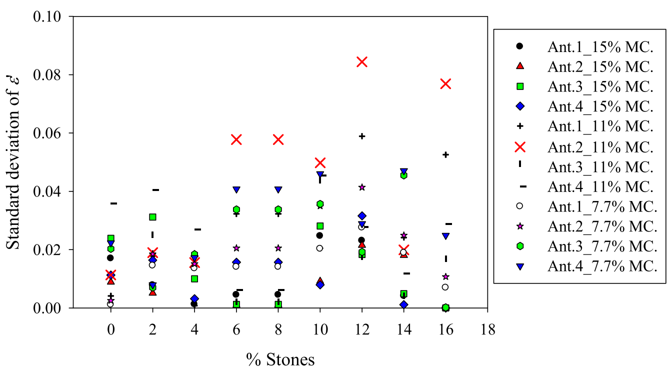


Fig. 16. Repeatability measurements for peanuts with peanut- raisins foreign material at room temperature (23 °C), (a) average value of ε', (a) standard deviation of ε', (c) average value of ε'' and (d) standard deviation of ε''.

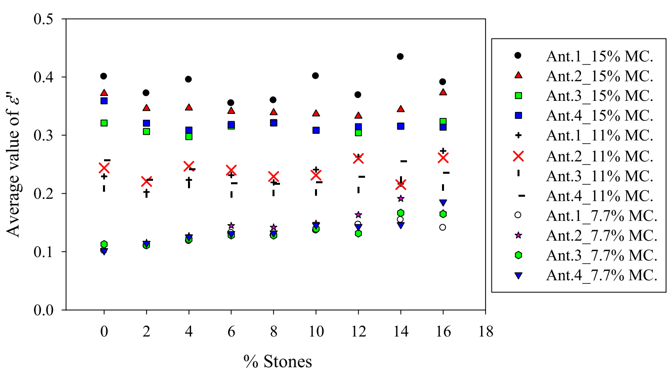
from each antenna or even from the same antenna for repeated measurements. Measurements were taken for three different loadings of the same sample into the sample container. Also, measurements were taken for two different orientations (180-degree rotation) of the sample container for each sample. Therefore, six measurements were carried out for each



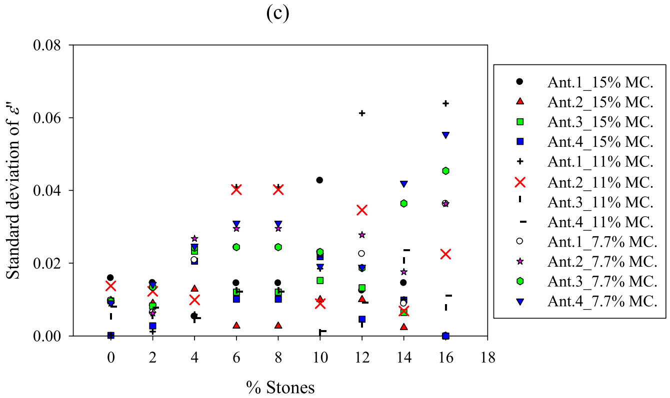
(a)



(b)



(c)



(d)

Fig. 17. Repeatability measurements for peanuts with stones foreign material at room temperature (23 °C), (a) average value of ε', (a) standard deviation of ε', (c) average value of ε'' and (d) standard deviation of ε''.

sample for evaluation of the measurement repeatability of each antenna and of all four pairs of antennas. The average value and the standard deviation of the dielectric properties were calculated for each antenna and are plotted in Figs. 14 to 17, which Figs. 14 to 17 show the measurement repeatability of each antenna for unshelled peanut samples with peanut shells, sticks, peanut raisins and stones, respectively. Only three moisture contents (7.7%, 11% and 15%) were plotted for purpose of clarity. Standard deviations (all antennas) of ε' and ε'' slightly increased with foreign material because of high dielectric contrast between unshelled peanuts and foreign materials. However, for peanut raisins mixed with unshelled peanuts, the standard deviations are flat and lower than for other foreign materials due to the similarity of the dielectric properties of peanut raisins is similar to unshelled peanut (low moisture content). For peanut shells or sticks mixed with unshelled peanuts, the standard deviations of ε'' slightly increased with the moisture content because of higher dielectric contrast between the unshelled peanuts (15% MC) and the foreign materials. The standard deviation of stones mixed with unshelled peanuts slightly increased when the moisture content of unshelled peanuts decreased. This means that higher measurement repeatability of ε'' can be expected at the lower moisture contents for unshelled peanut mixed with peanut shells or sticks while it can be expected at higher moisture content for unshelled peanuts mixed with stones.

Also, measurement repeatability can be observed by comparing the average value of the dielectric properties from the four pairs of antennas in Fig. 14 to 17. Higher variation between for each antenna was found at the higher moisture contents. This means that repeatability for each antenna decreased with moisture content. However, the measurement results from each antenna can be used for sensing the foreign materials at each position, especially, when the foreign materials are randomly distributed. In this instance, predicting the percentage of foreign material from each antenna would be more interesting because of higher sensitivity.

V. Conclusion

A free-space dielectric properties measurement for foreign materials detection in unshelled peanuts was designed based on a low-cost Yagi-Uda printed antenna and tested at 10 GHz. The four pairs of Yagi-Uda printed antennas were used to increase the measurement resolution for the unshelled peanut samples with foreign material in a 22cm × 22cm × 12cm sample container. The free-space measurement was achieved by using the IQ-demodulation technique together with microwave switching circuits connected to four pairs of Yagi-Uda printed antennas. The dielectric properties were extracted from the attenuation and phase shift measurements obtained from the IQ-demodulator. Permittivity measurements on plastic dielectric slabs of three different thicknesses agreed well with measurements obtained with horn-lens antennas and vector network analyzer. The proposed system with four pairs of Yagi-Uda printed antennas provides means for measurement in a small volume by measuring different materials in a partitioned sample container (4.5cm × 4.5cm × 12cm). Moreover, measurement results for moisture content determination (7.75% to 16%) on cleaned unshelled peanuts were accurate with a standard error of calibration (*SEC*) of 0.51%. Results of dielectric properties, repeatability measurements on unshelled peanuts with foreign materials such as sticks, peanut shells, peanut raisins and stones indicate good potential for free-space measurement with four pairs of Yagi-Uda printed antennas for real-time nondestructive sensing of foreign materials content in unshelled peanuts. This would be very useful in the peanut industry.

Acknowledgment

The authors would like to thank Dr. Stuart O. Nelson for his insightful comments and suggestions. They also express their appreciation to Anna Thurmond, student worker, University of Georgia, for conscientious effort in helping with the measurements.

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