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Sugar and water contents of honey with dielectric property sensing

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ABSTRACT

The dielectric properties of pure yellow locust, jujube and rape flower honey and their water-adulterated products with water content from 18% to 42.6% were measured with open-ended coaxial-line probe technology and a network analyzer from 10 to 4500 MHz at 25 °C. Dielectric constants of pure honeys and water-added honey samples decreased monotonically with increasing frequency, and increased with increasing water content. Dielectric relaxation was evident in the dielectric loss factors. The critical frequency and the maximum loss factor increased with increasing water content. There were strong linear correlations between the dielectric constant and the total soluble solids and water contents. The linear coefficients of determination were higher than 0.995 from 650 to 960 MHz. The good linear correlations and the sufficient penetration depth >20 mm below 960 MHz, suggest that microwave dielectric properties could be used in developing sensors to determine sugar and water contents.

1. Introduction

Honey is a sweet, viscous, and natural complex liquid food product with sought after flavor. It is produced by honeybees from the nectar of flowers. Bee honey has significantly nutritional and medical benefits with readily available sugars, organic acids, various amino acids and some biological active components such as α-tocopherol, ascorbic acid, and flavonoids (Turhan et al., 2008). International food regulations stipulate that honey is a pure product that does not allow for addition of any other substance (Diacu and Tantaveanu, 2007), including, but not limited to, water and other sweeteners. However, honey adulteration is a common phenomenon, especially in certain areas of the world. The adulteration leads to reduced nutritional value of honey, and thereafter, could cause health concerns to the consumers who rely on nutrients from honey products. Therefore, detection of honey adulteration is required to ensure quality and human safety. Currently, honey quality is measured by sensory and chemical analyses. The sensory analysis mainly detects honey color, viscosity, smell, flavor and crystallization. The accuracy of this method is limited and usually is influenced by sensory panelists and their experiences. The chemical analysis mainly includes chromatography, optical analysis, electroanalytical methods and mass spectrometry. Expensive instruments, complicated procedures and process time make chemical analysis impractical in the industry. Therefore, the development of a simple, rapid and low cost honey quality sensor is needed.

Dielectric properties or permittivities are intrinsic properties that determine the interaction of electromagnetic energy with materials. They are commonly represented by a complex number, the relative complex permittivity $\varepsilon^* = \varepsilon' - j\varepsilon''$, where the real part ε' (dielectric constant) is associated with the capability of energy storage in the material, and the imaginary part ε'' (loss factor) associated with energy dissipation in the material in the form of heat. Knowledge of the dielectric properties of various agri-foods and biological materials are finding increasing applications, and dielectric property measurement techniques have been adapted for use in various industries and research laboratories (Venkatesh and Raghavan, 2005). Extensive work has been done on a large number of agricultural products and foods, and shows that the electromagnetic wave frequency (García et al., 2004; Guo et al., 2007a,b,c; Ragni et al., 2007; Tanaka et al., 2005), and food compositions, especially moisture content (Kraszewski et al., 1999; Mabrook and Petty, 2003; Martín-Esparza et al., 2006; Tanaka et al., 2005; Trabelsi and Nelson, 2004), are the most important factors influencing materials' dielectric properties.

In honey adulterations, water is the most common ingredient. Water is also the most important ingredient affecting the dielectric properties of a material. It is very interesting to study how water influences the dielectric properties of honey, and to determine whether the dielectric properties could be used for determining water content or sugar content in honey and to detect water adulterations. So far, only limited information is available on dielectric

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properties of honeys. The dielectric properties of honey–water mixture were investigated using the time-domain reflectometry technique from 10 MHz to 10 GHz at 25 °C by Puranik et al. (1991). It was found that the addition of water to honey leads to a decrease in the relaxation time, and the relaxation time decreased with increasing water content. However, the correlations between the dielectric properties and sugar content and between the dielectric properties and water content in honeys were not studied. Ahmed et al. (2007) measured physical properties of several Indian pure honeys, but only dielectric properties in the frequency range of 900 to 2550 MHz were reported. However, they did not study the influence of water content on honey dielectric properties. The objectives of our present study are (1) to investigate the dielectric properties of honeys from 10 to 4500 MHz at 25 °C; (2) to study the effect of water on dielectric properties of honeys; (3) to determine the best frequency for establishing the relationship between dielectric properties and water and sugar contents; and (4) to estimate whether the relationship found can be used to predict honey sugar content and/or water content in practice.

2. Materials and methods

2.1. Honeys

Yellow locust flower honey, jujube flower honey and rape flower honey, packed in glass bottle by Shaanxi Dangdai Honey Industry Co. Ltd., were purchased from a local supermarket in Yangling, Shaanxi, China. The initial water contents of the samples used in the study were controlled at 18% by the corporation, and the samples were regarded as pure honeys. The main sugar compositions of the samples are listed in Table 1.

2.2. Dielectric properties measurements

The dielectric properties were measured with an Agilent Technologies 85070B open-ended coaxial-line probe and an Agilent Technologies E5071C vector network analyzer (Agilent Technologies, Malaysia). Dielectric constant and loss factor were calculated with Agilent Technologies 85070D dielectric probe kit software according to the reflection coefficient of the material in contact with the active tip of the probe. Settings were made to provide 101 measurements on a logarithmic scale from 10 to 4500 MHz. Before measurement, the E5071C Network Analyzer was calibrated with an open, short, and matched load in sequence at the port used for the measurement. Next, the cable for the 85070E open-ended coaxial-line probe was connected to the calibrated port. The computer program Agilent Connection Expert was initiated, which connects the network analyzer and the computer before initiating the 85070C computer program to perform the instrument setup. The dielectric probe was calibrated by using air, short-circuit, and 25 °C deionized water. A measurement was made on 25 °C deionized water to verify the performance of instruments after the calibration. When the probe was immersed in the deionized water during calibration and measurement, an effort was made to avoid air bubbles between water and the probe surface. During the experiment, any movement or change with the rigid cable used to connect the analyzer and the probe was avoided, since any subtle movement could affect measurement results.

Table 1
The main sugar compositions of three pure honeys used in the study.

Honey	Glucose (%)	Fructose (%)	Sucrose (%)	Total content (%)
Yellow locust	32.29	45.31	1.94	79.54
Jujube	33.90	40.50	1.66	76.06
Rape	40.34	37.66	1.75	79.75

2.3. Procedures

Known amount of deionized water was added to 70 ml pure honey, with 18% initial water content, of each kind to prepare the adulterated honey samples with different final water contents (22.1%, 26.2%, 30.3%, 34.4%, 38.5% and 42.6%, w/w) at room temperature. Masses of deionized water and honeys were determined with an FA2104A electronic balance (Shanghai Precision Scientific Instrument Co. Ltd., Shanghai, China) with precision of 0.0001 g. The samples were stirred with a glass stick slowly to mix the water and honey evenly. Total soluble solids content (or Brix) of honey samples were determined by a WYT refractometer (Chengdu Xingchenguang Optical Instrument Ltd., Chengdu, China) and were used as an indicator for sugar content. Three replicates were made on each sample. The mean and standard deviation values were used in the reported results.

Each beaker of 10 ml, filled with pure honey or water-adulterated honey solution up to a depth of 30 mm, was placed on a platform of 50 mm in diameter, and then was raised up until the downward open-ended coaxial-line probe was completely immersed in the sample. Honey is a very viscous fluid, and air bubbles are easily trapped. Any air bubble between the probe and samples interfaces with proper permittivity determination. For yellow locust, jujube and rape flower honeys used in this study, since they are transparent, air bubbles can be easily seen. Therefore, when no bubble was observed between the probe and sample, dielectric property measurements at 101 frequencies from 10 to 4500 MHz were performed in 1 min. Three replications for each sample were made. Between replications, the probe was washed with water and wiped dry. Our preliminary test results showed that the beaker size did not influence honey permittivities. All measurements were conducted at 25 ± 1 °C. After obtaining permittivities and total soluble solids content of each sample, the linear relationships between permittivities, i.e., dielectric constant and dielectric loss factor, and total soluble solids content, and between permittivities and water content were regressed at 101 discrete frequencies from 10 to 4500 MHz.

2.4. Penetration depth

Penetration depth, d_p, of radio frequency and microwave power is defined as the depth where the power is reduced to $1/e$ ($e = 2.7183$), about 37%, of its value at the surface of the material. The d_p value in meter in a lossy material can be calculated (Metaxas and Meredith, 1993) as follows:

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)}} \tag{1}$$

where c is the speed of light in free space (3×10^8 m/s), f is the frequency in Hz, ε' and ε'' are obtained dielectric constant and loss factor of a material, respectively. Once the dielectric properties have been obtained, the penetration depth of electromagnetic energy in the selected materials can be calculated at the required frequency.

3. Results and discussion

3.1. The frequency dependence of dielectric properties of pure honeys

The measured dielectric properties of three kinds of pure honey over the frequency range from 10 to 4500 MHz at 25 °C are illustrated in Fig. 1. The results reveal that the permittivities of the

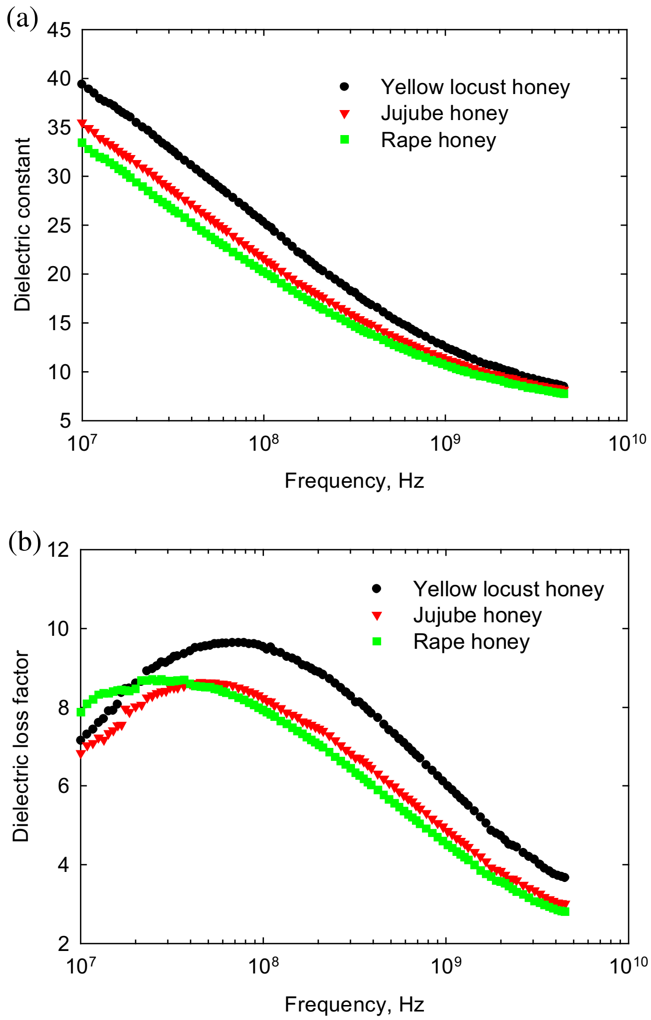

Fig. 1. The dielectric properties of pure honeys with 18% water content over the frequency range from 10 to 4500 MHz at 25 °C.

three different honeys had the same frequency dependence. The dielectric constants decreased monotonically with increasing frequency. The yellow locust honey had the highest dielectric constant, and the rape honey had the lowest value at a given frequency. The dielectric loss factors reveal an overriding dielectric relaxation behavior. The highest loss factor for yellow locust honey, jujube honey and rape honey were 9.64, 8.63, and 8.70, and appeared at the critical frequencies, where the highest loss factor is, about 70, 45 and 30 MHz, respectively. The mechanisms that contribute to the dielectric loss in heterogeneous mixtures include polar, electronic, atomic and Maxwell–Wagner response (Metaxas and Meredith, 1993). Although the pure honey contains water, the water is in bound form (Puranik et al., 1991). The dielectric relaxation is likely resulted from bound water according to the frequency where critical frequency appeared in honey (Hasted, 1973). The relaxation behavior of loss factor was also noticed when permittivities were measured on external surfaces of fruits, such as apple (Guo et al., 2007a), honeydew melon (Guo et al., 2007b), and watermelon (Nelson et al., 2007), and on walnut kernels (Wang et al., 2003).

In addition, the dielectric constants and loss factors presented here show the similar trend and values as those of Indian honeys with the similar total soluble solid contents between 900 and 2550 MHz (Ahmed et al., 2007). The compositions and properties of honeys are mainly dependent on floral origins, climatic conditions of the producing areas, processing and storage (Turhan et al., 2008). Even though honeys have similar total soluble solids content, other compositions can also influence their dielectric properties greatly, such as ash contents (Ahmed et al., 2007). This makes it very difficult to compare permittivity values of different pure honeys.

3.2. The influence of water content on dielectric properties of honeys

The influence of water content on the dielectric properties of yellow locust honey is presented in Fig. 2. No matter how much water content (18–42.6%) was in yellow locust honey or honey solution, the dielectric constant decreased with increasing frequencies (Fig. 2a). The dielectric constant increased with increasing water content at any given frequency, and pure honey had the lowest dielectric constant. Moreover, the increasing water content slowed the decrease of the dielectric constant with increasing frequency. For pure honey, the dielectric constant decreased more rapidly at lower frequencies and tapered slowly with increasing frequency. For the honey solution with 42.6% water content, the dielectric constant decreased slowly at lower frequency and more rapidly with increasing frequency.

Fig. 2b shows that the critical frequencies, f_c, of the dielectric loss factor shifted to higher frequencies with increasing water content. This result was coherent with the decrease of relaxation time with increasing water content, found by Puranik et al. (1991). Fur-

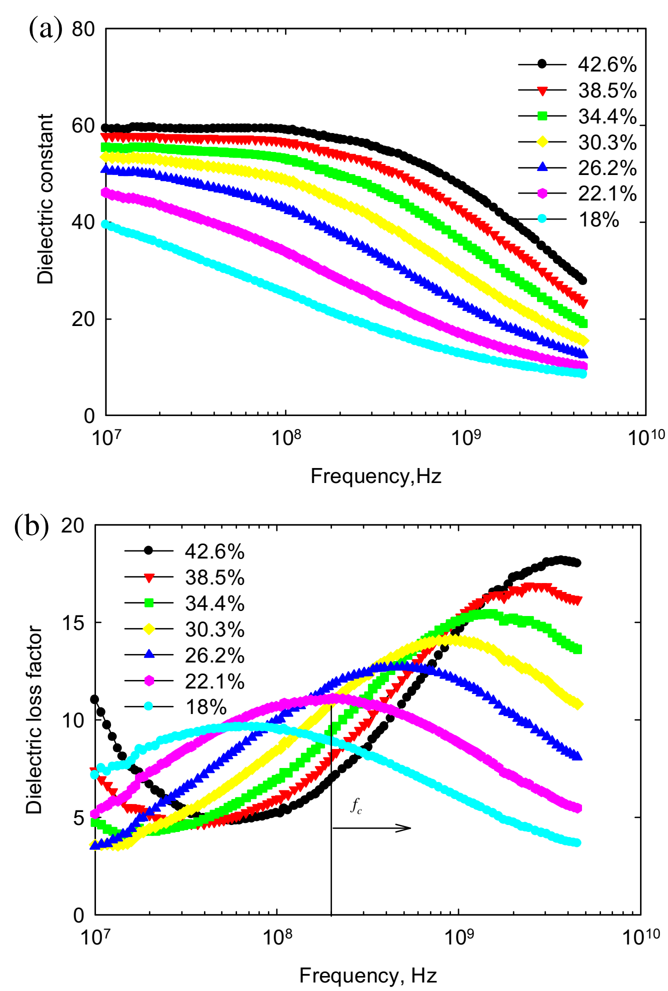

Fig. 2. The influence of water content on the dielectric properties of yellow locust honey over the frequency range from 10 to 4500 MHz at 25 °C.

thermore, the maximums of loss factor at the critical frequencies also increased with water content. For example, the critical frequencies appeared at about 200, 915 and 2450 MHz for honey solutions with water content of 22.1%, 30.3% and 38.5%, and the maximums of loss factor were 11.1, 14.1 and 16.9, respectively. It is predicted that the critical frequency and the maximum loss factor will increase with increasing water content in honey, but they will be less than 18.02 GHz and 36.7, respectively (Kaatze, 1989), which are pure water critical frequency and the highest loss factor at 25 °C. The critical frequency shifting phenomena was also found when adding water to vinegar or soy sauce (Tanaka et al., 2002, 2005). For example, when the mixture ratio changed from 1:0 to 1:4 (soy sauce:deionized water), the soy sauce had 70% moisture content originally, the relaxation wavelength decreased from 0.0668 to 0.0348 m at 20 °C, corresponding to a critical frequency increase from 4.49 to 8.62 GHz.

Unlike honey, the critical frequency shifting phenomenon with water content was not obvious in milk (Nunes et al., 2006). The reason is that milk had 89–92% water (Nunes et al., 2006) and most of it is free water, however, the honey only had 18% water in mainly bound form.

Another obvious change in loss factor was found at the lower frequencies, i.e., about 20 MHz. In this frequency range, if the water content ⩽26.2%, the loss factor decreased with increasing water content, otherwise, it increased with increasing water content.

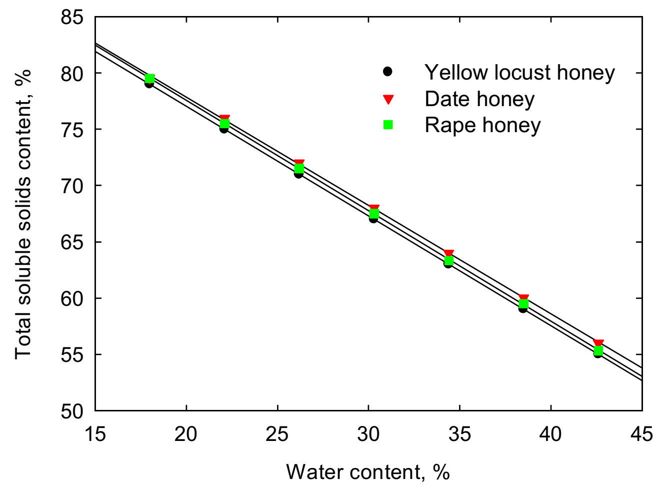

Fig. 3. Linear regression of total soluble solids content on water content for honey solutions at 25 °C.

Table 2
The dielectric constant (ε') and loss factor (ε'') with standard deviation of pure honeys (18%) and honey solutions with different water contents at four selected frequencies at 25 °C.

Honey	Water content (%)	Permittivity	Frequency (MHz)			
			10	915	2450	4500
Yellow locust	18	ε'	39.41 ± 0.23	12.92 ± 0.02	9.84 ± 0.02	8.47 ± 0.03
		ε''	7.15 ± 0.33	6.25 ± 0.02	4.44 ± 0.01	3.66 ± 0.01
	22.1	ε'	46.09 ± 0.27	17.17 ± 0.12	12.27 ± 0.04	10.10 ± 0.02
		ε''	5.18 ± 0.47	9.07 ± 0.14	6.68 ± 0.10	5.48 ± 0.07
	26.2	ε'	50.78 ± 0.21	23.46 ± 0.14	15.99 ± 0.10	12.51 ± 0.07
		ε''	3.50 ± 0.13	12.18 ± 0.04	9.76 ± 0.06	8.10 ± 0.06
	30.3	ε'	53.46 ± 0.19	30.00 ± 0.16	20.35 ± 0.12	15.43 ± 0.07
		ε''	3.59 ± 0.31	14.10 ± 0.03	12.58 ± 0.07	10.81 ± 0.07
	34.4	ε'	55.43 ± 0.20	36.67 ± 0.11	25.47 ± 0.10	19.03 ± 0.09
		ε''	4.74 ± 0.19	14.92 ± 0.05	15.08 ± 0.05	13.62 ± 0.05
	38.5	ε'	57.73 ± 0.18	42.80 ± 0.13	30.98 ± 0.14	23.28 ± 0.13
		ε''	7.40 ± 0.29	14.83 ± 0.04	16.89 ± 0.02	16.16 ± 0.05
	42.6	ε'	59.33 ± 0.23	47.92 ± 0.26	36.30 ± 0.28	24.75 ± 0.26
		ε''	11.01 ± 0.28	14.06 ± 0.11	17.90 ± 0.09	18.19 ± 0.10
Jujube	18	ε'	35.48 ± 0.40	11.68 ± 0.03	9.22 ± 0.02	8.15 ± 0.01
		ε''	6.84 ± 0.68	5.06 ± 0.02	3.60 ± 0.01	3.00 ± 0.01
	22.1	ε'	42.54 ± 0.84	14.21 ± 0.30	10.57 ± 0.23	8.99 ± 0.21
		ε''	6.63 ± 0.28	7.17 ± 0.13	5.12 ± 0.10	4.19 ± 0.08
	26.2	ε'	51.18 ± 1.20	21.75 ± 2.16	15.14 ± 0.92	12.18 ± 0.01
		ε''	5.63 ± 0.46	11.14 ± 0.02	8.70 ± 0.02	7.21 ± 0.01
	30.3	ε'	52.87 ± 0.12	26.87 ± 0.11	18.40 ± 0.07	14.31 ± 0.05
		ε''	6.73 ± 0.24	12.90 ± 0.03	11.03 ± 0.05	9.39 ± 0.04
	34.4	ε'	56.11 ± 0.27	34.40 ± 0.19	23.91 ± 0.18	18.14 ± 0.15
		ε''	9.97 ± 0.32	14.42 ± 0.09	14.04 ± 0.07	12.57 ± 0.08
	38.5	ε'	58.89 ± 0.13	40.66 ± 0.39	29.20 ± 0.37	22.12 ± 0.31
		ε''	14.81 ± 0.45	14.80 ± 0.04	16.12 ± 0.10	15.19 ± 0.16
	42.6	ε'	62.02 ± 0.15	46.64 ± 0.23	34.86 ± 0.24	26.66 ± 0.21
		ε''	21.11 ± 0.52	14.65 ± 0.06	17.75 ± 0.04	17.68 ± 0.08
Rape	18	ε'	33.42 ± 0.33	10.97 ± 0.01	8.68 ± 0.01	7.74 ± 0.01
		ε''	7.87 ± 0.47	4.70 ± 0.01	3.31 ± 0.01	2.81 ± 0.01
	22.1	ε'	44.36 ± 0.27	17.60 ± 0.06	12.48 ± 0.05	10.12 ± 0.04
		ε''	5.72 ± 0.35	9.21 ± 0.05	6.93 ± 0.04	5.87 ± 0.03
	26.2	ε'	48.22 ± 0.30	22.52 ± 0.15	15.36 ± 0.09	11.92 ± 0.07
		ε''	4.57 ± 0.22	11.67 ± 0.06	9.39 ± 0.06	7.98 ± 0.06
	30.3	ε'	52.71 ± 0.18	28.73 ± 0.41	19.46 ± 0.31	14.66 ± 0.22
		ε''	5.11 ± 0.33	13.79 ± 0.04	12.10 ± 0.14	10.54 ± 0.16
	34.4	ε'	57.24 ± 0.20	37.48 ± 0.10	26.31 ± 0.11	19.66 ± 0.10
		ε''	7.27 ± 0.40	14.92 ± 0.04	15.19 ± 0.01	14.06 ± 0.03
	38.5	ε'	57.70 ± 0.59	42.47 ± 0.51	30.80 ± 0.45	23.03 ± 0.36
		ε''	10.26 ± 0.31	14.76 ± 0.11	16.72 ± 0.16	16.30 ± 0.20
	42.6	ε'	60.62 ± 0.28	48.48 ± 0.06	36.49 ± 0.08	27.53 ± 0.08
		ε''	14.69 ± 0.33	14.56 ± 0.05	18.32 ± 0.02	18.86 ± 0.02

These changes may be due to ionic conduction. Added water in honey decreases its viscosity and binding forces to ionic movement, therefore, the ionic conduction plays a growing role in the loss mechanism as the water content is gradually increased. It has been found and demonstrated that the ionic conduction is the dominated loss mechanism in foods, such as in fruits (Nelson, 2005; Wang et al., 2005), meat (Wang et al., 2008), and egg (Guo et al., 2007c), in radio frequency range, and its role makes the loss factor be inversely proportional to frequency.

The water content dependence of dielectric properties of jujube honey and rape honey was similar to that of yellow locust honey. Table 2 shows the measured average and standard deviation permittivities of the honeys or honey solutions with different water contents at the selected frequencies of 10, 915, 2450, and 4500 MHz.

3.3. The relationship between dielectric properties and quality indices

The best criterion for honey quality is sugar content. The sugar content is reduced after water is added, and the sweetness is decreased. Fig. 3 shows linear regression of total soluble solids content on water content for the three tested honeys. As expected, there was obvious negative linear relationship between total soluble solids content and water content. The linear coefficients of determination (R^2) for yellow locust, jujube and rape flower honey were 1.000, 0.999 and 0.999, respectively. If without regard to honey varieties, the total soluble solids content still was strongly correlated with water content with R^2 of 0.999.

It was also found that there were very strong linear correlations between the dielectric constant at almost all frequencies and total soluble solids content as well as water content. Figs. 4 and 5 present the linear regressions of dielectric constant at 915 MHz on total soluble solids content and on water content of yellow locust honey, respectively. The linear relationships can be described as

$$\varepsilon' = k_1 S + c_1 \quad (2)$$

$$\varepsilon' = k_2 W + c_2 \quad (3)$$

where S and W, in percent, represent total soluble solids content and water content, respectively. k_1 and c_1 are slope and intercept of regressed line in Fig. 4, respectively, and k_2 and c_2 are slope and intercept of regressed line in Fig. 5, respectively. The regressed constants and linear coefficients of determination, R^2, in Eqs. (2) and (3) at selected four frequencies for the three honeys from 10 to 4500 MHz at 25 °C are listed in Table 3.

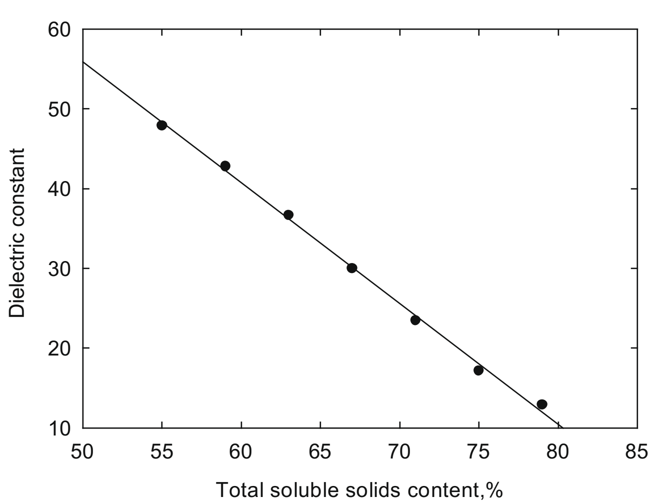

Fig. 4. Linear regression of dielectric constant at 915 MHz on total soluble solids content of yellow locust honey.

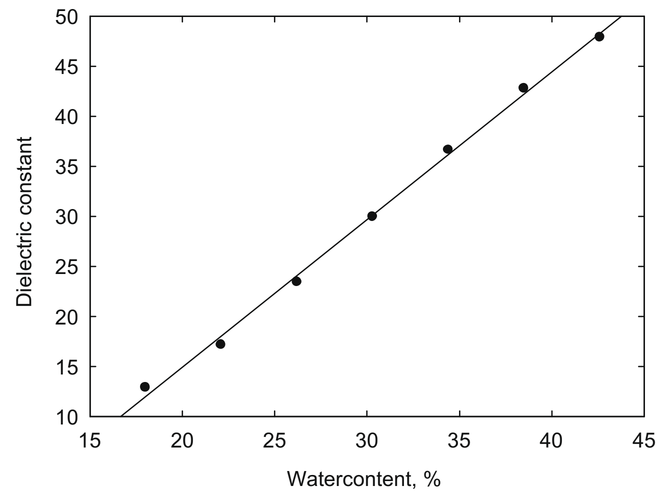

Fig. 5. Linear regression of dielectric constant at 915 MHz on water content of yellow locust honey.

Fig. 6 is the linear coefficients of determination between the dielectric constant and total soluble solid content at 101 detected frequencies from 10 to 4500 MHz for yellow locust honey. The R^2 in Eqs. (2) and (3) for jujube and rape honey at a given frequency are very similar to that of yellow locust honey.

In the studied frequency range, the R^2 between the dielectric constant and total soluble solids content and between the dielectric constant and water content were higher than 0.91 for all the three honeys. The highest R^2, 0.997, 0.996 and 0.997, appeared at 780–960 MHz, 650–720 MHz and 720–960 MHz for yellow locust, jujube and rape honey, respectively. If taking no account of honey species, all data of the three pure honeys and their water-adulterated samples were regressed together, the strong linear correla-

Table 3
The regressed constants and coefficients of determination in Eqs. (2) and (3) at four selected frequencies for yellow locust, jujube and rape flower honeys at 25 °C.

Honey	Constants and R^2	Frequency (MHz)			
		10	915	2450	4500
Yellow locust	k_1	−0.793	−1.513	−1.127	−0.81
	c_1	104.20	131.54	97.15	70.92
	R^2 (2)	0.931	0.997	0.986	0.975
	k_2	0.764	1.746	1.100	0.790
	c_2	28.602	−14.59	−11.737	−7.291
	R^2 (3)	0.931	0.997	0.986	0.975
Jujube	k_1	−1.057	−1.544	−1.115	−0.795
	c_1	123.11	132.94	95.92	69.84
	R^2 (2)	0.928	0.994	0.982	0.974
	k_2	1.021	1.485	1.071	0.764
	c_2	20.352	−16.958	−12.269	−7.361
	R^2 (3)	0.935	0.992	0.978	0.970
Rape	k_1	−1.041	−1.573	−1.163	−0.825
	c_1	120.83	135.83	99.82	72.03
	R^2 (2)	0.911	0.996	0.986	0.977
	k_2	1.022	1.544	1.141	0.810
	c_2	19.649	−17.035	−13.209	−8.148
	R^2 (3)	0.912	0.996	0.986	0.976
All honeys	k_1	−0.958	−1.545	−1.136	−0.811
	c_1	115.87	133.54	97.77	71.01
	R^2 (2)	0.902	0.994	0.984	0.976
	k_2	0.936	1.502	1.104	0.788
	c_2	22.867	−16.207	−12.405	−7.560
	R^2 (3)	0.906	0.989	0.978	0.970

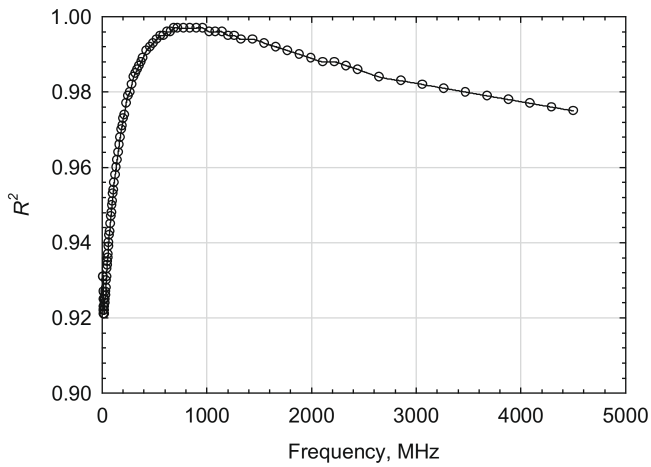

Fig. 6. The linear coefficients of determination, R^2, between dielectric constant and total soluble solids content of yellow locust honey from 10 to 4500 MHz at 25 °C.

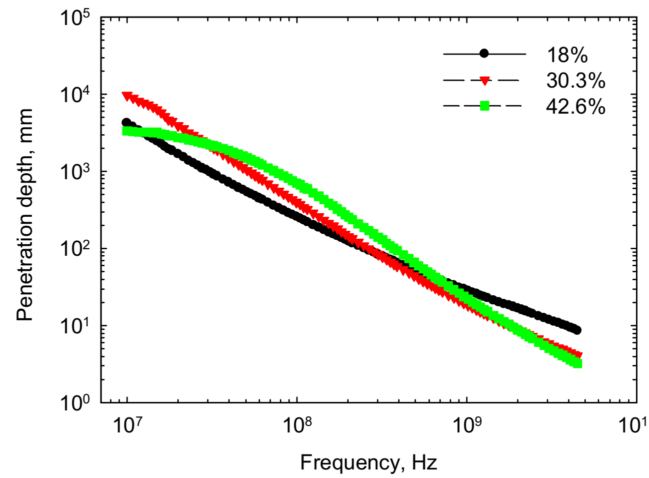

Fig. 7. The effect of water content on penetration depth over the frequency range from 10 to 4500 MHz at 25 °C.

tions between the dielectric constant and total soluble solids content and between the dielectric constant and water content still existed. The highest R^2, 0.995, was between 650 and 960 MHz. The regressed results at selected frequencies are presented in Table 3. These strong correlations suggest that the dielectric constant can be used to accurately predict sugar content and water content of honey samples according to following equations:

$$S = \frac{\varepsilon' - c_1}{k_1} \tag{4}$$

$$W = \frac{\varepsilon' - c_2}{k_2} \tag{5}$$

3.4. The penetration depth of honey

Strong linear correlations between dielectric property and total soluble solids content as well as water content in honeys show a potential for developing dielectric spectral-based sensor for honeys. However, the penetration depth of the electromagnetic energy in the selected materials must be considered before the dielectric properties can be used in sensing honey quality in practice.

The calculated penetration depths from the measured dielectric properties of the pure yellow locust honey (18%) and honey solution samples with water content of 30.3% and 42.6% over the frequency range from 10 to 4500 MHz at 25 °C are shown in Fig. 7. For the pure honey and the honey sample with 30.3% water, the penetration depth decreased with increasing frequency linearly in log–log plot. At the low frequency (10 MHz), the penetration depth increased with increasing water content up to a maximum after which it decreased with increased water content. For example, it was 4802, 9738 and 3354 mm for pure yellow locust honey and honey samples having 30.3% and 42.6% water content at 10 MHz. At the high frequency (4500 MHz), the penetration depth continuously decreased with increasing water content. The penetration depths of the honeys with different water content at 10, 915, 2450 and 4500 MHz at 25 °C are listed in Table 4.

The highest linear coefficients of determination between dielectric constant and total soluble solids content and between dielectric constant and water content were from 650 to 960 MHz. At that frequency range, the penetration depths for the three honeys were higher than 20 mm. This depth should be sufficient to conduct dielectric property measurements in the development of a practical and rapid sensor for the predication of sugar or water contents in honeys in practice.

Table 4
Penetration depth, in mm, of pure honeys (18%) and honey samples with different water contents at four selected frequencies at 25 °C.

Honey	Frequency (MHz)	Water content (%)						
		18	22.1	26.2	30.3	34.4	38.5	42.6
Yellow locust	10	4802	6274	9741	9738	7510	4916	3354
	915	31.3	25.0	21.7	21.1	21.9	23.7	26.4
	2450	14.2	10.6	8.4	7.3	6.8	6.7	6.8
	4500	8.6	6.4	4.9	4.1	3.6	3.3	3.2
Jujube	10	4180	4716	6080	5173	3602	2495	1807
	915	36.6	28.7	22.9	21.9	22.0	23.2	25.0
	2450	16.8	12.8	9.1	7.9	7.1	6.8	6.7
	4500	10.3	7.8	5.3	4.5	3.8	3.5	3.3
Rape	10	3532	5572	7262	6793	4978	3550	2550
	915	38.2	24.9	22.2	21.1	22.1	23.7	25.6
	2450	17.7	10.3	8.5	7.4	6.9	6.7	6.6
	4500	10.7	6.0	4.8	4.1	3.5	3.3	3.1

4. Conclusions

Measurements of dielectric constant and dielectric loss factor of yellow locust, jujube and rape flower pure honeys and water-adulterated honey samples were conducted with open-ended coaxial-line probe technology and a network analyzer over the frequency range from 10 to 4500 MHz at 25 °C. The dielectric constants of pure honeys and honey solutions decreased with increasing frequency in the studied frequency range, and increased with water content. Dielectric relaxation was evidenced in the dielectric loss factor. The critical frequency shifted to higher end with increased water content, and the maximum loss factor at the critical frequency increased as well. There were very strong linear correlations, $R^2 > 0.995$, between dielectric constant and total soluble solids content and water content at 650–960 MHz. The penetration depth of electromagnetic energy in honeys decreased with increased frequency, and it was higher than 20 mm for honeys when the frequency was lower than 960 MHz. The strong linear correlations between dielectric constant and total soluble solids content and dielectric constant and water content, and the sufficient penetration depths indicate that permittivities have potential application in sensing honey sugar content and water content in practice, and can be developed into a rapid and simple honey sugar or water content sensors to examine honey products in food processing and marketplace.

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