Low-cost portable dielectric spectrometer based on mini-vector network analyzer and open-ended coaxial probe technology

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Abstract: As a simple, fast, and non-destructive measuring technology, dielectric spectroscopy is usually used to analyze the dielectric properties of agricultural products and food, and then to predict the main components of materials. However, the large and expensive vector network analyzers (VNA) with expensive analysis software applied in measuring dielectric properties make research limited to the laboratory. To acquire dielectric spectra in situ, a model for solving relative complex permittivity was derived, and its performance was validated. Then, a low-cost portable dielectric spectrometer with a mini VNA, a Raspberry Pi, and a coaxial probe as core parts was developed over the frequency range of 100-3000 MHz. The stability and accuracy of the developed spectrometer were tested using milk and juice. The results indicated that the relative errors of the model were within ±5% for dielectric constant (ε') and loss factor (ε''). The coefficients of variation of measured ε' and ε'' by the developed spectrometer at 100-3000 MHz were less than 1% and 2%, respectively. Compared with the dielectric properties obtained by using a commercial dielectric measurement system, the relative errors of measured ε' and ε'' were within ±3.4% and ±6.0%, respectively. This study makes fast, non-destructive, and on-site food quality detection using dielectric spectra possible.
Keywords: coaxial probe, mini vector network analyzer, low-cost, portable, dielectric spectrometer
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1 Introduction

Dielectric properties refer to the response properties of a material to an external electric field. They are the real and imaginary parts of relative complex permittivity ε_r^*, defined as:

$$\varepsilon_r^* = \frac{\varepsilon^*}{\varepsilon_0} = \varepsilon' - j\varepsilon'' \quad (1)$$

where, ε^* is the complex permittivity, and ε_0 is the vacuum permittivity with the value of 8.854×10^{-12} F/m[1]. The dielectric constant ε' reflects the ability of a material to store charges, and the loss factor ε'' shows the ability of a material to consume electromagnetic field energy[2]. Numerous studies have shown that the dielectric properties of agricultural products and food are not only dependent on the frequency of the applied electric field and the sample's temperature but also closely related to their constituents[3]. For instance, the dielectric properties of milk are influenced by its main components, such as fat[4], protein[5], and lactose[6]. Since the dielectric properties are related to the compositions of materials, and the measurement of dielectric properties is rapid and non-destructive, dielectric spectroscopy has been widely applied in the quality detection of various agricultural products and food.

The methods used to collect dielectric spectra mainly include parallel plate[7], open-ended coaxial probe[8], resonant cavity[9], free space[10], and transmission line[11]. Owing to the advantages of easy sample preparation, good reproducibility, and wide frequency range, the dielectric properties are mainly collected by bench-top vector network analyzer (VNA) applied in laboratories with matched open-ended coaxial probe and measurement software, such as E5071C produced by Agilent Technologies Inc[12]. Although these VNAs could offer accurate dielectric properties in a wide frequency range and in a short time, their large size and high price cause the current research on dielectric properties to be mainly in laboratories.

With the emergence of various low-cost portable VNAs, such as ShockLine MS46121B VNA of Anritsu Corporation, Planar R54 VNA of Copper Mountain Technology, and mini VNA produced by Mini Radio Solutions, it is possible to obtain the dielectric spectra of materials and to predict the quality of agricultural products and food in situ. However, the lack of matched low-cost commercial coaxial probes and measurement software causes these devices to be difficult to widely apply in collecting dielectric spectra of agricultural products and food. To provide a solution for rapid, non-destructive, and on-site detection of the quality of agricultural products and food using dielectric spectra, a calculation model for the relative complex permittivity was derived in this study, and the performance of this model was verified by electromagnetic simulation software. Then, a low-cost portable dielectric spectrometer was developed with a Raspberry Pi as a controller, a cheap mini VNA as a dielectric spectra acquisition module, and a homemade low-cost coaxial probe as a test probe. Finally, the measurement performance of the developed dielectric spectrometer was evaluated.

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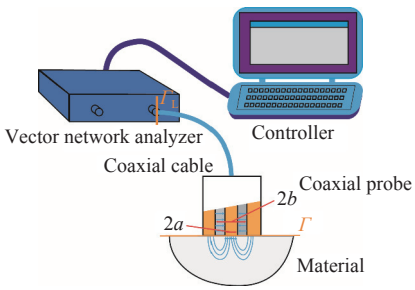
2 Materials and methods

2.1 Calculation model of relative complex permittivity

The principle of the coaxial probe measurement system is shown in Figure 1. It mainly consists of a controller, a VNA, a coaxial cable, and an open-ended coaxial probe. The coaxial probe is a waveguide constituted by two coaxial cylindrical conductors. The radius of the inner conductor is a, and the inner radius of the hollow outer conductor is b. The gap between the two cylinders is filled with a dielectric material, such as Teflon.



Note: a is the radius of the inner conductor, m; b is the inner radius of the hollow outer conductor, m; Γ is the reflection coefficient of the coaxial probe port.

Figure 1 Schematic diagram of the coaxial probe measurement system

For calculating the relative complex permittivity, four standard samples, i.e., deionized water, air, short circuit, and normal saline, were used as standard samples 1, 2, 3, and 4, respectively. As the coaxial probe port was terminated by these standard and testing samples, the corresponding reflection coefficients were measured by VNA, which were marked as Γ_1, Γ_2, Γ_3, Γ_4, and Γ_L, respectively.

All components between the VNA and coaxial probe port are equivalent to a two-port network, and the standard sample 3 was a short circuit. Therefore, the aperture admittance Y_L, which is the admittance of the coaxial probe port contacted with the testing sample can be expressed as[13]:

$$Y_L = (Y_1 + \Delta Y_2)/(1 + \Delta) \tag{2}$$

where, Y_1 and Y_2 are aperture admittances when the probe is contacted with deionized water and air, respectively. Of which, $\Delta = \dfrac{(\Gamma_L - \Gamma_1)\times(\Gamma_3 - \Gamma_2)}{(\Gamma_L - \Gamma_2)\times(\Gamma_1 - \Gamma_3)}$.

Based on the quasi-static model, when the probe is contacted with a semi-infinite medium area, Y_L can be derived as[14]:

$$Y_L \approx j\frac{2\omega I_1}{\left[\ln(b/a)\right]^2}\varepsilon^* - j\frac{\omega^3\mu_0 I_2}{\left[\ln(b/a)\right]^2}\varepsilon^{*2} + \frac{\pi\omega^4\mu_0^{3/2}}{12}\left[\frac{b^2-a^2}{\ln(b/a)}\right]^2\varepsilon^{*5/2} \tag{3}$$

where, a and b are the inner conductor radius and outer conductor inner radius of the coaxial probe, respectively; μ_0 is the free space permeability with the value of $4\pi\times10^{-7}$ N/A^2, ε^* is the complex permittivity of the semi-infinite medium, ω is the angular frequency of electromagnetic field, and I_1 and I_2 are two triple integral constants[10]. The third term in Equation (3) is radiation conductance, which can be ignored at lower microwave frequencies. Therefore, Equation (3) can be simplified as:

$$y_L \approx \varepsilon_r^* + \xi\varepsilon_r^{*2} \tag{4}$$

where, $y_L = \dfrac{Y_L[\ln(b/a)]^2}{j2\omega I_1\varepsilon_0}$, and $\xi = -\dfrac{\omega^2\mu_0 I_2\varepsilon_0}{2I_1}$.

Using the standard sample 4 as a testing sample, Equation (5) can be obtained by replacing Y_1, Y_2, and Y_L in Equation (2) with the y_1, y_2, and y_4, which are expressed in Equation (4) by the relative complex permittivity ε_{r1}^*, ε_{r2}^*, and ε_{r4}^* of standard samples 1, 2, and 4, respectively.

$$\varepsilon_{r4}^* + \xi\varepsilon_{r4}^{*2} = \left(\varepsilon_{r1}^* + \xi\varepsilon_{r1}^{*2} + \Delta'\left(\varepsilon_{r2}^* + \xi\varepsilon_{r2}^{*2}\right)\right)/\left(1 + \Delta'\right) \tag{5}$$

where, $\Delta' = \dfrac{(\Gamma_4 - \Gamma_1)\times(\Gamma_3 - \Gamma_2)}{(\Gamma_4 - \Gamma_2)\times(\Gamma_1 - \Gamma_3)}$.

The Cole-Cole model was used to calculate the relative complex permittivity of deionized water[15]. The relative complex permittivity of air is 1, and the relative complex permittivity of normal saline was measured by the dielectric properties measurement system composed of E5071C VNA, 85070B coaxial probe, and 85070E software (Agilent Technologies Inc., Malaysia). The procedures for measuring the dielectric properties of liquid materials could be found elsewhere[4]. Equation (6) is derived by replacing the standard sample 4 in Equation (5) using the testing sample. Then, the relative complex permittivity of the testing sample can be calculated by solving Equation (6).

$$\varepsilon_{rL}^* + \xi\varepsilon_{rL}^{*2} = \left(\varepsilon_{r1}^* + \xi\varepsilon_{r1}^{*2} + \Delta\left(\varepsilon_{r2}^* + \xi\varepsilon_{r2}^{*2}\right)\right)/\left(1 + \Delta\right) \tag{6}$$

2.2 Verification of model performance

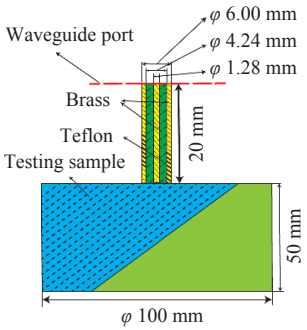
2.2.1 Software and materials

The software of CST 2019 (CST Co., Ltd., Germany), a 3D high-frequency electromagnetic field analysis and design software was used to simulate the coaxial probe to obtain Γ_L of the standard and testing samples, to calculate the relative complex permittivity, and to verify model performance. In the material library of CST, deionized water, air, and perfect electric conductor were selected as standard samples 1, 2, and 3 in the calculation model, respectively. When the standard sample is the perfect electric conductor, it means in a short circuit. New materials can be added to the material library of CST by inputting the Debye equation parameters of the materials. Since there is no reference for the parameters of normal saline in the Debye equation, the parameters of ethanol and methanol in the Debye equation are not only known but also used as a standard sample sometimes[16]. Therefore, ethanol and methanol were added into the material library of CST as the standard sample 4 and testing sample, respectively. All parameters in the Debye equation were described elsewhere[15].

2.2.2 Verification method on the derived model

Firstly, the simulation structure for the coaxial probe, shown in Figure 2a, was established using the structural modeling tool of CST. The upper part of the structure was a coaxial probe, and the lower part was a testing sample. The coaxial probe used in the subsequent development of the dielectric spectrometer was modified from an SMA-JFD coaxial connector (Shenzhen Chengtai Electronics Co., Ltd., China). Figures 2b and 2c show the coaxial connector and the obtained coaxial probe, respectively. The diameter of the inner conductor of the coaxial probe was 1.28 mm, and the inner and outer diameters of the outer conductor were 4.24 mm and 6.00 mm, respectively. The diameters of the inner and hollow outer conductors in the simulation structure were set according to the coaxial probe. Moreover, the height of the coaxial probe was set as 20 mm. The material of conductors was brass with a purity of 91%. Since the testing sample is not an ideal semi-infinite medium, to simulate the actual situation, the testing sample in the simulation was set as a cylinder with a diameter of 100 mm and a height of 50 mm. Before the simulation, the simulation frequency range, background, and boundary condition were set as 20-4500 MHz, normal, and default, respectively. To solve the reflection coefficient, a waveguide port was set up on the upper port of the coaxial probe. After setting the testing sample materials as

deionized water, air, perfect electric conductor, ethanol, and methanol, the frequency domain solver was applied to solve the reflection coefficient of each sample. Finally, the relative complex permittivity of methanol can be calculated based on Equation (6). The calculation results were compared with the reference relative complex permittivities obtained from the Cole-Cole model[15]. The relative error was used to evaluate the accuracy of the derived relative complex permittivity calculation model.



a. Simulation structure of coaxial probe

b. Coaxial connector

c. Coaxial probe

Figure 2 Schematic diagram of the simulation structure for coaxial probe built in CST, coaxial connector, and coaxial probe

3 Development of hardware and software for dielectric spectrometer

3.1 Development of hardware

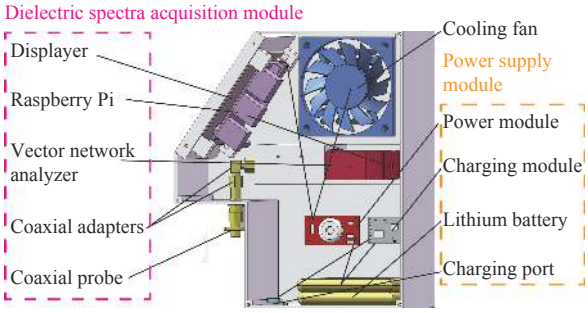
Figure 3a is the hardware schematic diagram of the developed portable dielectric spectrometer. The hardware consisted of a dielectric spectra acquisition module, a power supply module, and a mechanical structure.

3.1.1 Dielectric spectra acquisition module

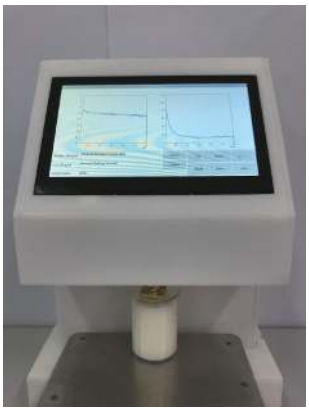
The dielectric spectra acquisition module was composed of a mini VNA (Shenzhen Xueli Electronics Co., Ltd., China), a Raspberry Pi 3B+ (Raspberry Pi Foundation, UK), a touch display (Shenzhen Waveshare Electronics Co., Ltd., China), two coaxial adapters, and a coaxial probe. The mini VNA was used to collect the reflection coefficient spectra. The frequency range and dynamic range of the mini VNA were 1-3000 MHz and 70 dB, respectively. As the main controller, the Raspberry Pi conducted the calibration of the VNA and the calculation of dielectric spectra. The touch display was connected to the Raspberry Pi through an HDMI interface and applied as an input and output device of the Raspberry Pi. Two coaxial adapters were used to connect the VNA and the coaxial probe.

3.1.2 Power supply module

The power supply module of the detector consisted of a lithium battery, a power module, a charging module, and a charging port. The capacity and nominal output voltage of the lithium battery were 20 Ah and 3.7 V. The output of the lithium battery was boosted to 5.0 V display, and the mini VNA was powered by the Raspberry Pi. The charging module was connected to the micro USB charging port to charge the lithium battery.



a. Schemetic diagram



b. Prototype

Figure 3 Schematic diagram and prototype of the dielectric spectrometer

3.1.3 Mechanical structure

The mechanical structure was used to house other components and provide a reasonable space arrangement. The vents were placed on the sidewall of the shell, and an Orico cooling fan (Shenzhen Original Times Technology Co., Ltd., China) was installed. To use easily, the display and the coaxial probe were arranged on the front of the housing. The Raspberry Pi was fixed on the back of the display. To ensure the heat is dissipated efficiently, the mini VNA was placed in the center of the housing, near the fan, and fixed on the sidewall of the housing by a bracket. To lower the height of the gravitational center, the lithium battery was arranged on the bottom of the instrument. The power module, charging module, and charging port were installed on the shell around the battery. The mechanical structure of the dielectric spectrometer was produced by 3D printing. The prototype of the dielectric spectrometer is shown in Figure 3b, which was 14 cm in length, 12 cm in width, 17 cm in height, and less than 1 kg in weight.

3.2 Development of software

Figure 4 shows the main interface of the data acquisition software. The software was developed on a personal computer using Spyder, Python 3.6, and the graphical user interface design toolkit Tkinter, and it can run on Raspberry Pi. At the bottom layer of the software, the vnaJ.3.2.10 program without a user interface was used to control the mini VNA for setting parameters and collecting the reflection coefficient. The main interface had four areas, which were the display area, input area, calibration area, and measurement and save area. The display area was used to display the collected reflection coefficient spectra and dielectric spectra. The input area was applied to input the data saving path, calibration file path, and file name. The calibration area was used to collect the reflection coefficient spectra of deionized water, air, short, and normal saline. The measurement and save area were applied to collect dielectric spectra and save collected data.

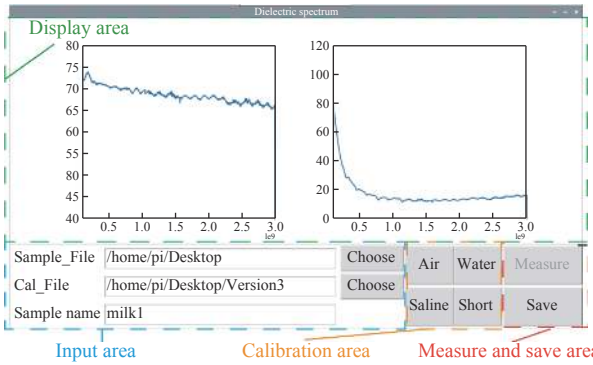


Figure 4 The main user interface of the data acquisition software

3.3 Measurement procedure

The detector was warmed up for about 20 min before application. Then, the coaxial probe was taken off, and the mini VNA was calibrated with open, short, and 50 Ω matched loads in sequence. All calibration steps were completed using vnaJ.3.2.10 software with a graphical user interface and the calibration file was saved in the set path. After the coaxial probe was installed, the data acquisition software was opened, then the spectral data path and calibration file path were selected. The coaxial probe was calibrated by air, deionized water, normal saline, and indium foil whose content of indium was larger than 99.999%. For liquid calibration or testing samples, the coaxial probe was immersed in the liquid sample contained in a beaker to a depth of about 2 mm. The beaker had a diameter of 22 mm and a height of 20 mm. The deepness of the sample was not less than 18 mm. When the indium foil or other solid samples were measured, the coaxial probe should be in contact with the sample closely. The calibration on the coaxial probe was conducted by clicking the corresponding buttons of "Air", "Water", "Saline" and "Short" in the calibration area to collect the reflection coefficient spectra of air, deionized water, normal saline, and indium foil, respectively. After calibration, a testing sample was put under the coaxial probe, and the "Measure" button in the measurement and save area was clicked to collect the reflection coefficient spectra of the testing sample. The relative complex permittivities were calculated automatically with the software based on Equation (6) and the collected reflection coefficient spectra of the standard samples and testing samples. Then, they were displayed in the display area. Finally, click the "Save" button to save the collected data.

3.4 Validation of the performance of the developed dielectric spectrometer

Commercial whole milk, low-fat milk, and prepared orange and grape juices were used as samples to validate the measurement performance of the developed dielectric spectrometer. The commercial whole and low-fat milk samples were produced by Yili Co., Ltd. The fat, protein, lactose, and total solids contents of used milk samples were measured by using Milkoscan™ FT1 (Foss Analytical A/S, Hillerød, Denmark). The orange and grape juices were obtained by squeezing fresh orange and grape using a juicer and filtered twice by a bag filter with a pore size of 1 mm. The soluble solids content (SSC), pH, and conductivity of the obtained juices were determined by using a PR101 digital refractometer (Atago Co., Ltd., Japan), PHSJ-3F pH meter (Shanghai Precision & Scientific Instrument Co., Ltd., China), and DDSJ-308A conductivity meter (Shanghai Precision & Scientific Instrument Co., Ltd., China), respectively. All measurements were performed at room temperature (25±1)°C. The fat, protein, lactose, and total solids contents of whole and low-fat milk samples were 3.96% and 1.48%, 3.31% and 3.67%, 4.73% and 5.24%, and 12.46% and 11.16%, respectively. The SSC, pH, and conductivity of orange and grape juices were 10.00% and 14.5%, 3.93 and 3.58, and 2.3 mS/cm and 2.1 mS/cm, respectively.

The whole milk was used as the representative sample to evaluate the stability of the developed dielectric spectrometer. Its dielectric spectra were collected every 3.0 min in 1.5 h with the self-made dielectric spectrometer. The sample temperature was kept at 25°C using a constant-temperature water bath. A thermometer was used to check the sample temperature. The coefficients of variation of the data at each investigated frequency were calculated based on the results of 30 measurements[17].

The accuracy of the dielectric spectrometer was evaluated by the two milk samples and two juice samples. Each sample was divided into two parts. One part was used to obtain the dielectric spectra by E5071C VNA matched with 85070B coaxial probe and 85070E software (Agilent Technologies Inc., Malaysia). Another part was used to collect the dielectric spectra by the self-developed dielectric spectrometer. Five replicates were done for each sample, and the averages were used as the results. Since there were obvious noises in the original spectra obtained by the developed dielectric spectrometer, the locally weighted scatter curve smoothing technique was used to preprocess the dielectric spectra[18]. The accuracy of the dielectric spectrometer was evaluated by the relative errors between the obtained dielectric properties using the dielectric spectrometer and E5071C VNA.

4 Results and discussion

4.1 Model verification

Figure 5a shows the ε' and ε'' spectra of methanol between 20 MHz and 4500 MHz calculated based on CST simulation and Cole-Cole model. The ε' and ε'' spectra of methanol obtained by CST simulation had slight fluctuation at the frequencies below 1000 MHz. In general, the dielectric spectra of methanol obtained based on CST simulation were highly coincident with those calculated based on the Cole-Cole model in the whole frequency range.

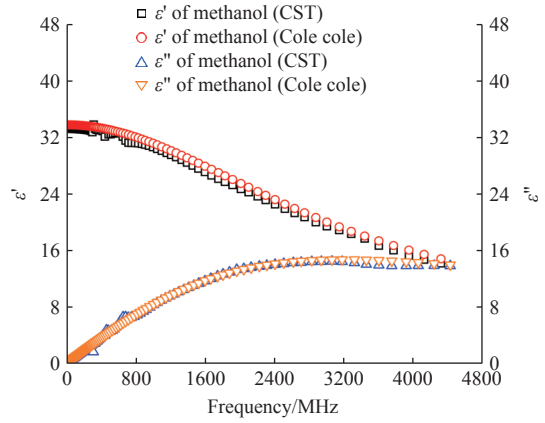
Figure 5b shows the relative errors of ε' and ε'' of methanol obtained using CST simulation to their reference spectra which were calculated using the Cole-Cole model. In the whole frequency range, the relative errors of simulated ε' and ε'' of methanol were between −4.8% and 0.2% and between −4.8% and 1.5%, respectively. The results indicated that the relative errors of the simulated ε' and ε'' versus that calculated values using the Cole-Cole model were within ±5%, indicating that the constructed model can accurately calculate the relative complex permittivity based on the measured reflection coefficient.

4.2 Performance validation of portable dielectric spectrometer

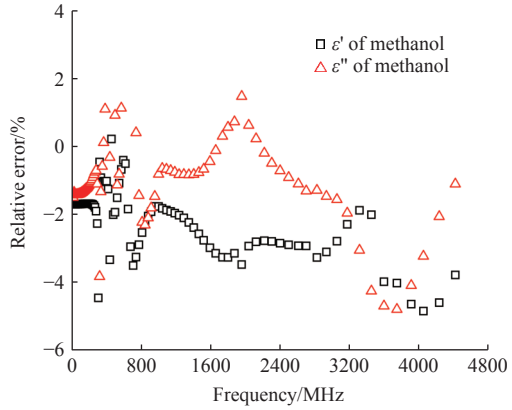
4.2.1 Stability

Figure 6a shows the ε' and ε'' spectra of whole milk in 30 collections within 1.5 h at 25°C. In the whole frequency range, the ε' generally decreased with the increase of frequency. The ε'' decreased rapidly below about 500 MHz, and increased slowly above about 1500 MHz. The minimum values of ε'' appeared around 1500 MHz.

Figure 6b shows the coefficients of variation of the dielectric properties at each investigated frequency. In the whole frequency range, the coefficients of variation of ε' and ε'' were less than 1% and 2%, respectively. Especially between 200 and 1250 MHz, no matter for ε' or ε'', the coefficients of variation were about 1%. This indicated that the developed dielectric spectrometer had good stability in the whole frequency range, especially at the low-frequency end.

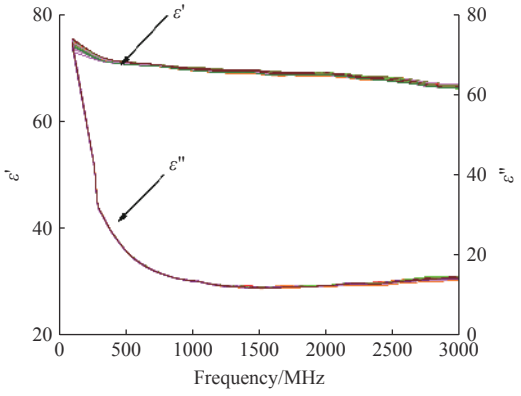


a. Simulated dielectric spectra

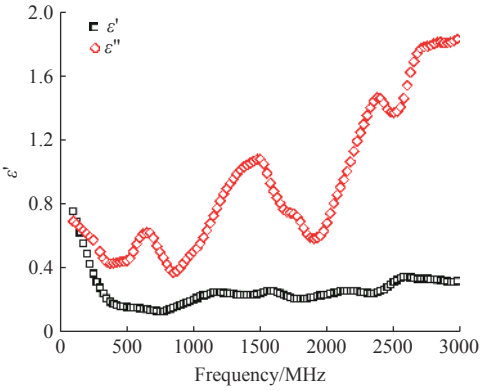


b. Relative errors

Figure 5 Simulated dielectric spectra using CST and relative errors of methanol versus that calculated using the Cole-Cole model



a. Collected dielectric spectra

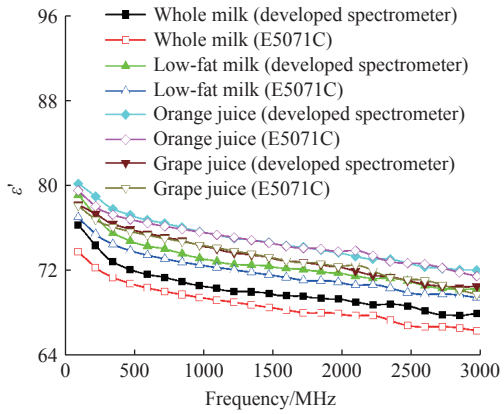


b. Coefficients of variation

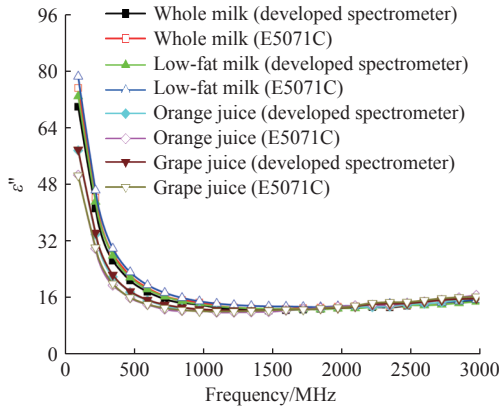
Figure 6 Collected dielectric spectra and coefficients of variation of whole milk in 1.5 h with an interval of 3 min

4.2.2 Accuracy

Figure 7 shows the ε' and ε'' spectra of whole milk, low-fat milk, orange juice, and grape juice in the frequency range of 100-3000 MHz measured by the self-made dielectric spectrometer and E5071C VNA. The obtained ε' (Figure 7a) or ε'' (Figure 7b) spectra using the two instruments had the same trend with frequency, i.e., with the increase of frequency, the ε' decreased slightly with increased frequency, and the ε'' decreased rapidly at the low-frequency end and increased slightly above 1500 MHz.



a. ε'



b. ε''

Figure 7 The spectra of ε' and ε'' of milk and juices measured by the self-made dielectric spectrometer and E5071C VNA

There are a lot of polar molecules in milk and juice. When the frequency is low, the polar molecules can change with the direction change of the electric field. As the frequency increases, some dipoles will no longer be able to keep up with the change of direction of the electric field. Therefore, the ε' decreases with increasing frequency[1]. For samples with high water content, ion conduction, and dipole relaxation are the main loss mechanisms[2]. When ion conduction plays a major role, the ε'' decreases rapidly as the frequency increases. When the main mechanism changes from ion conduction to dipole polarization, the ε'' will slowly increase with the increase of frequency. This phenomenon is also found in the dielectric properties of other juices[12] and fresh milk[19].

Comparing the two types of milk, the ε' of whole milk was lower than that of low-fat milk. The fat content of whole milk (3.96%) was higher than that of low-fat milk (1.48%). Fat is an inert substance with dielectric properties. Previous studies have shown that the ε' of milk decreased with the increase in fat content[4]. When the ε' of orange and grape juices were compared, the orange juice had a higher ε', which might be caused by the higher SSC of orange juice (14.5%) than that of grape juice (10.0%). Higher SSC means

more particles in juice, which could hinder the movement of polar molecules, causing decreased ε' with increased SSC[20].

When the frequency was lower than 1250 MHz, the ε'' of low-fat milk was higher than that of whole milk, and the ε'' of orange juice was higher than that of grape juice. It is known that ionic conduction is the main loss mechanism at low frequencies[21], but it was reduced owing to the fat globules and SSC, which hindered the movement of ions in the liquid samples. Slight differences between ε'' of whole milk and low-fat milk or between ε'' of orange and grape juices at 1250-3000 MHz tell that the dipole polarization, which dominates the dielectric loss at microwave frequency, contributed almost equally to milk or juice.

Comparing the results obtained by the two instruments, the dielectric spectra collected by the self-made dielectric spectrometer were close to the data obtained by the E5071C VNA. Figure 8 shows the relative errors of the self-made dielectric spectrometer compared with the E5071C VNA. For whole and low-fat milk, the relative errors of ε' were 1.4%-3.4% and 0.6%-2.8%, respectively, and the relative errors of ε'' were −6.0%-3.0% and −6.0%-0.5%, respectively. For orange juice and grape juices, the relative errors of ε' were −0.8%-1.2% and −0.8%-0.8%, respectively, and the relative errors of ε'' were −6.0%-1.0% and −5.5%-3.0%, respectively.

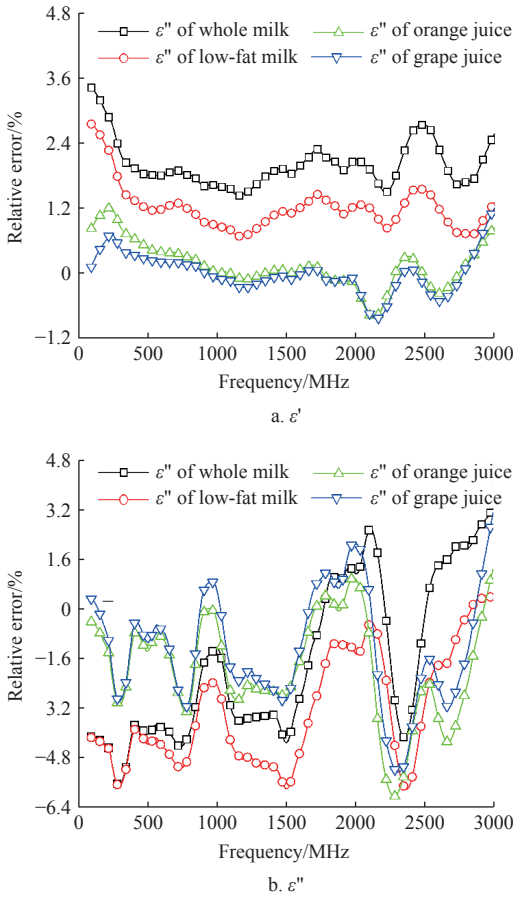


Figure 8 Relative errors of ε' and ε'' of milk and juices measured by the developed dielectric spectrometer versus that obtained using E5071C VNA

When the two materials were compared, the measurement errors for milk were slightly larger than those for juice. The fat in milk is in the form of fat globules, which are strong scatters to electromagnetic waves. The scattering affects the stability of the measurement results[22]. The fat content in whole milk was higher than that of low-fat milk, causing more serious scattering and resulting in higher errors for whole milk than for low-fat milk.

In general, for liquid samples with high dielectric loss, the measurement results of the dielectric spectrometer developed in this research matched well with those obtained by using VNA applied in laboratories. In the whole frequency range, the relative error of the dielectric spectrometer was within ±3.4% for ε' and was within ±6.0% for ε''. The relative error for the ε'' was higher than that for the ε'.

5 Conclusions

A calculation model for relative complex permittivity based on open-ended coaxial probe technology was introduced and verified with CST simulation software in this study. Compared with the theoretical values calculated with the Cole-Cole model, the relative errors of the derived model were within ±5% both for ε' and ε''. A low-cost portable dielectric spectrometer over the frequency range of 100-3000 MHz was developed mainly by using the mini VNA. The spectrometer had good stability with coefficients of variation less than 1% and 2% for ε' and ε'', respectively. Especially below 1250 MHz, the coefficients of variation were about 1%. The relative error of the developed dielectric spectrometer was within ±3.4% for ε' and was within ±6.0% for ε''. The measurement time for each sample was less than 40 s. The developed portable dielectric spectrometer provides a solution for measuring dielectric properties in situ and also offers an implementation scheme for rapid, non-destructive, and on-site quality detection of agricultural products and food with the dielectric spectra. In the future, the accuracy and stability of the developed dielectric spectrometer will be improved to fit practical applications. Recently, several studies have investigated the feasibility of dielectric spectra in the determination of internal qualities such as fat, protein, and lactose of raw milk. Therefore, a portable detector on main compositions of milk will be developed based on this dielectric spectrometer.

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