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Characterisation and analysis of alcohol in baijiu with a microwave cavity resonator

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ABSTRACT

The world's most consumed liquor-baijiu is characterised by measuring the perturbation in the resonance condition of a cylindrical microwave cavity as a function of alcohol content. Compared with other methods, the microwave sensor described here is compact, portable, low-cost and need of a small sample size (<0.1 mL) of liquid. The dielectric properties are obtained from the shift of the resonance frequency and changes in the quality factor. The measurement accuracy is validated by comparison with standard liquid samples, where high estimation accuracy (better than 6%) is achieved. The resonant responses and permittivity of baijiu samples are evaluated, where the alcohol content has a significant effect. Six other types of alcoholic drinks and ethanol-water mixtures were also measured for comparison purposes. From all the experimental results, it is demonstrated that the alcohol by volume can be readily deduced from the regressed functions obtained. In addition, the principal component analysis is successfully applied to the classification of liquids with varied alcohol contents.

1. Introduction

Baijiu, a clear colourless Chinese liquor with alcohol by volume (ABV) between 35% and 60%, is the most consumed spirit worldwide. It is usually distilled from fermented sorghum, wheat or barley (Fang, Du, Jia, & Xu, 2018). For evaluation of the quality of baijiu, conventional methods of sensory and chemical analysis can be used. However, the accuracy given by the sensory analysis is limited and suboptimal. The chemical analysis methods (e.g., gas chromatography (He & Jeleń, 2021), high-performance liquid chromatography (Zhang, Wang, Wang, Yang, et al., 2020), ultra-performance liquid chromatography (Chen et al., 2020), mass spectrometry (Zhang, Wang, Wang, Chen, & Xu, 2020), near-infrared or ultraviolet spectroscopy (Yang et al., 2019)) involve expensive equipment, trained personnel and time-consuming processing. Besides, in-situ characterisation cannot be provided by these methods. Therefore, the development of sensors that can provide more convenient and efficient assessment is required.

Recently, increased attention has been paid to microwave techniques for food analysis, as they have the advantages of low cost, quick data collection (few minutes rather than hours), low signal power consumption (up to few milliwatts) and ease of fabrication (Gibson et al., 2008). Over the microwave range, the electromagnetic field interacts with polar molecules and/or ions. The amounts of energy reflection and absorption are determined by the electric permittivity (also called dielectric properties), which is a complex number, i.e., $\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0(\varepsilon_r' - j\varepsilon_r'')$. ε_0 is the permittivity of free space, and ε_r is the relative permittivity. The real part ε_r', or dielectric constant, is associated with the capability of energy storage, while the imaginary part ε_r'', or loss factor, represents the ability of energy absorption in the form of heat. Every food has unique permittivity, and the information provided by dielectric characterisation is useful for microwave processing (Metaxas & Meredith, 1993) and quality control. Some food properties can be obtained from the permittivity changes, such as added water in food (Kent, Knöchel, Daschner, & Berger, 2001), the water content in milk (Zhao, Liu, & Zhang, 2019; Zhu & Guo, 2020), adulteration in oil (Cataldo, Piuzzi, Cannazza, & De Benedetto, 2012; Zhang, Chen, Jing, Dong, & Yu, 2019) and honey (Guo, Zhu, Liu, & Zhuang, 2010; Zhen Li, Haigh, Soutis, Gibson, & Sloan, 2017; Zhen Li, Meng, Haigh, Wang, & Gibson, 2021). Research on the topic of alcohols has also been reported, such as red grape juice and red wine (García, Torres, De Blas, De Francisco, & Illanes, 2004), vermouth (Bohigas & Tejada, 2010), beer

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Table 1
Information of the Chinese baijiu samples measured.

Brand	Jiangxiaobai	Niulanshan	Diaoxiangcun	Guyue	Hongxing	Hongxing
Place of origin (City in China)	Chongqing	Beijing	Yichang	Shaoxing	Beijing	Beijing
ABV (%)	40	42	45	50	53	56
Code	BJ-40	BJ-42	BJ-45	BJ-50	BJ-53	BJ-56

Table 2
Other typical alcoholic drinks measured for comparison with baijiu.

Alcohol type	Huangjiu (Yellow wine)	Shochu	Soju	Brandy	Whisky	Vodka
Brand	Guyue	Ryugin	Bohae	Zhangyu	Ballantine's	Grafskaya
Place of origin	Shaoxing, China	Gero, Japan	Jangseong, Korea	Yantai, China	Scotland, UK	Nowy Tomyśl, Poland
ABV (%)	≥10	15	17.3	38	40	96

Table 3
Equivalent ABV values of the ethanol-water mixtures converted from the volume fractions.

ζ (vol%)	10	20	30	40	50	60	70	80	90
ABV (%)	10.04	20.29	30.73	41.24	51.72	62.06	72.22	82.07	91.51

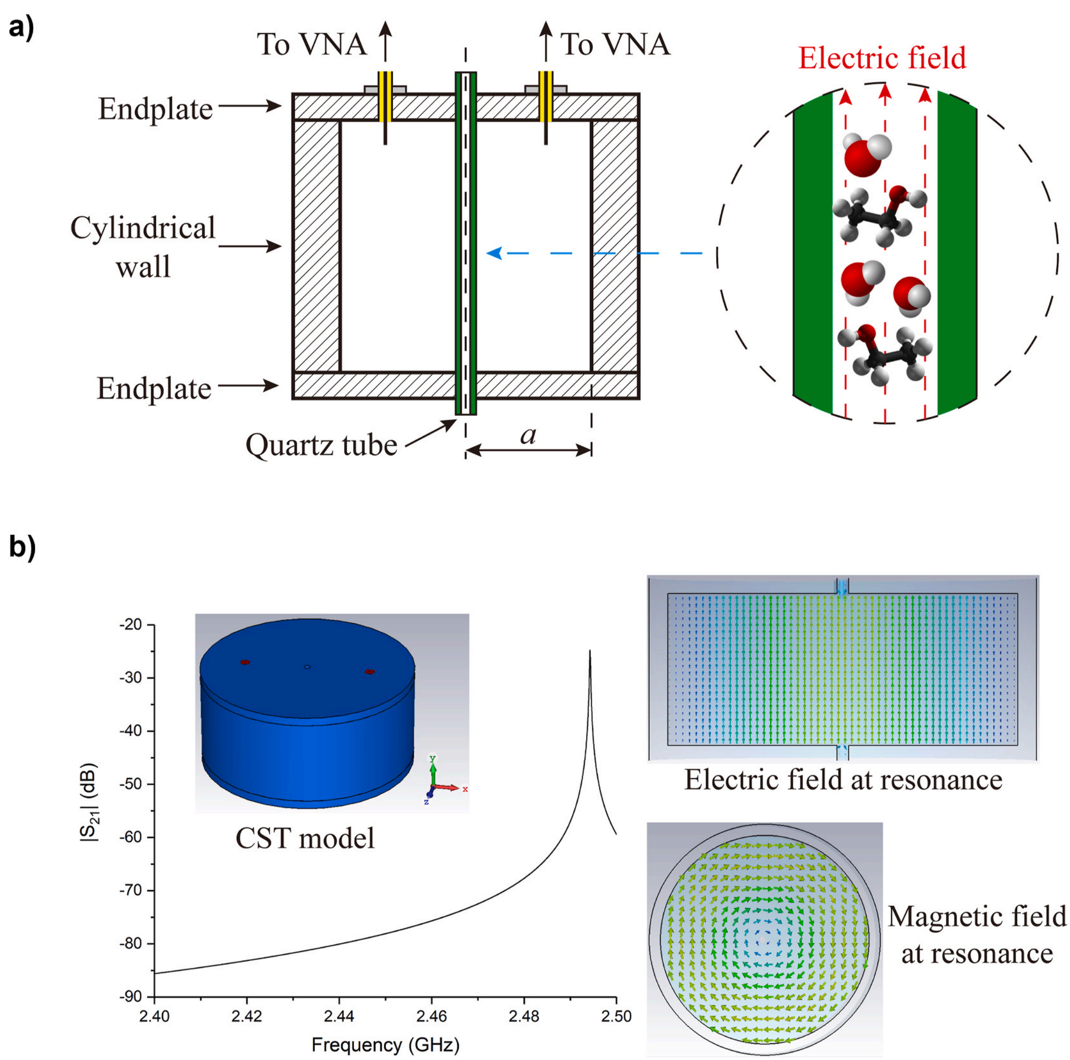

Fig. 1. TM_{010} mode cylindrical cavity resonator developed: (a) cross section; (b) electromagnetic simulation model and results including the frequency responses and the field distributions at resonance.

(Velázquez-Varela, Castro-Giráldez, & Fito, 2013), tequilas (Kataria, Sosa-Morales, Olvera-Cervantes, & Corona-Chavez, 2017) and rum (Rodríguez-Moré, Lobato-Morales, Chávez-Pérez, & Medina-Monroy, 2018), the ABV values of which are generally low. However, very little work on high-ABV alcoholic drinks like baijiu can be found in the literature. Only some preliminary study was performed by Li, Wang, Raghavan, and Vigneault (2011). It was found that the permittivity was strongly related to the ethanol content in baijiu. More work is required to reveal the quantitative correlation between the permittivity and the ethanol content.

The objectives of this study are to: 1) measure the permittivity of baijiu using a resonance approach. In the existing work on alcoholic drinks discussed, a commercial dielectric probe was commonly used. The probe is very expensive (Keysight, 2020), and it is produced for scientific research only. Here a low-cost cavity resonator sensor is used. The resonance method is adopted, as it requires relatively easy sample preparation and can provide higher possible accuracy than the other permittivity measurement methods (i.e., transmission line, open-ended and free space measurements) (Krupka, 2006). Standard samples with known permittivity are assessed for verification. 2) investigate the effect of the alcohol content on the permittivity. Baijiu samples with varied ABV values, other types of alcoholic drinks and ethanol-water mixtures are characterised. The resultant resonant responses (i.e., resonance frequency and quality factor) and permittivity are analysed. 3) study the effect of the alcohol content on the raw signals received. The principal component analysis (PCA) is employed for feature extraction.

2. Materials and methods

2.1. Liquid samples

Distilled water, ethanol (≥99.8% purity) (Sinopharm Chemical Reagent Co., Ltd, Shanghai, China), 0.05 M, 0.10 M and 0.15 M NaCl solutions (the purity of sodium chloride used was at least 99.8%) were used as standard liquids to check the accuracy of the sensor system. Six bottles of baijiu and bottles of six other types of alcoholic drinks were purchased from a local supermarket. The brands, places of origin and ABV values shown on the packaging are presented in Table 1 and Table 2. Each baijiu sample is represented by BJ-X, where X is the corresponding ABV value. Ethanol-water mixtures were also prepared at room temperature (25.5 ± 1.0 °C), and the ethanol volume fractions (ζ) were from 10% to 90% with an interval of 10%. For better comparison with baijiu, as given in Table 3, the volume fractions are converted to ABV (ABV is defined as the number of millilitres of pure ethanol present in a 100 mL solution at 20 °C) considering the excess volume and the temperature difference. The conversion is performed by

$$\mathrm{ABV} = \xi \rho_m^{20}(\xi) / \rho_e^{20} \tag{1}$$

where ξ is the mass fraction of ethanol in the mixture. ρ_m^{20} and ρ_e^{20} are the densities of the ethanol-water mixture and pure ethanol at 20 °C, respectively. Both ρ_m^{20} and ρ_e^{20} can be looked up in a handbook of chemistry (e.g., Speight, 2005). ρ_m^{20} is a function of ξ, which can be calculated at the test temperature T

$$\xi = \frac{\rho_e^T V_e^T}{\rho_e^T V_e^T + \rho_w^T V_w^T} = \frac{\rho_e^T \zeta}{\rho_e^T \zeta + \rho_w^T (1 - \zeta)} \tag{2}$$

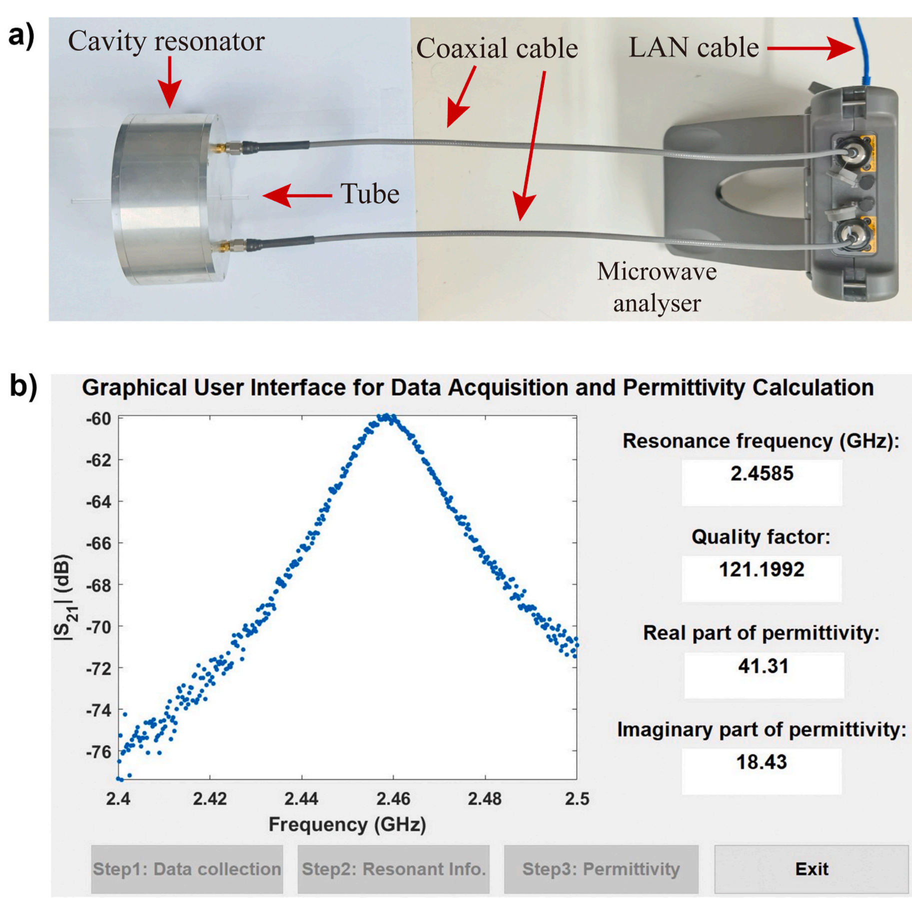

Fig. 2. Experimental setup for the evaluation of liquid samples using the microwave resonator sensor: (a) photograph; (b) graphical user interface for easy data acquisition and processing.

where ρ_e^T and ρ_w^T are the densities of the pure ethanol and water at T, respectively. The reference data of ρ_e^T and ρ_w^T can also be found in the literature. V_e^T and V_w^T are the volumes of pure ethanol and water used in the preparation at T, respectively.

2.2. Cavity resonator sensor and signal processing

The resonant cavity sensor was made of aluminium alloy 6061 (commonly used machine grade aluminium). As illustrated in Fig. 1(a), it consists of a cylindrical wall and two endplates. A liquid-filled fused quartz tube with a small cross-sectional area (outer diameter of 3 mm) can be inserted through a hole at the centre of each endplate. Six circularly spaced M2 threaded holes were made at each end of the cylinder, and accordingly six holes with a slightly larger diameter (2.2 mm) were drilled in each endplate. The wall and endplates were joined by socket screws. The resonant cavity is operated in the TM_{010} mode, which is widely used for permittivity measurement. CST® software is employed for electromagnetic simulation. The results of the empty cavity are presented in Fig. 1(b), where the resonance exists at 2.49420 GHz and the quality factor Q is approximately 12620. In this mode, the magnetic field only has the azimuthal component, while the electric field is parallel to the cavity axis and circularly symmetric.

Two groups of data are analysed in the present work: the resonance frequency and quality factor of the cavity directly extracted from the curve of the transmission coefficient (S_{21}); the permittivity of the sample under test. With the introduction of the liquid-filled tube, the resonant responses are changed accordingly. Relative complex permittivity estimation formulae deduced from the perturbation theory are given (Chen, Ong, Neo, Varadan, & Varadan, 2004; Slocombe, Porch, Bustarret, & Williams, 2013):

$$\varepsilon_r' = \frac{r_2^2}{r_1^2}\left[1 + 0.5392\frac{a^2}{r_2^2}\frac{f_1 - f_2}{f_1} - \left(1 - \frac{r_1^2}{r_2^2}\right)\varepsilon_{rq}'\right] \tag{3a}$$

$$\varepsilon_r'' = \frac{r_2^2}{r_1^2}\left[0.2696\frac{a^2}{r_2^2}\left(\frac{1}{Q_2} - \frac{1}{Q_1}\right) - \left(1 - \frac{r_1^2}{r_2^2}\right)\varepsilon_{rq}''\right] \tag{3b}$$

where f_1 and f_2 are the resonance frequencies before and after the material perturbation, respectively. Q_1 and Q_2 are the quality factors before and after the perturbation, respectively. $a = 46$ mm is the radius of the cavity, and the height of the cavity is 40 mm $r_1 = 0.50$ mm and $r_2 = 1.50$ mm are the inner and outer radii of the quartz tube, respectively. $\varepsilon_{rq} = \varepsilon_{rq}' - j\varepsilon_{rq}''$ is the relative permittivity of the tube, and the reference value at 25 °C and 2.50 GHz, i.e., 3.78-j2.30 $\times 10^{-4}$ (Hippel, 1995), is adopted. For known a, r_1, r_2, f_1 and Q_1, a higher f_2 is related to a lower ε_r'; similarly, a higher Q_2 corresponds to a lower ε_r''. Assumptions are made for obtaining Equations (3a) and (3b), i.e., the magnitude of the electric field in the cavity is not disturbed before and after the perturbation, and a small change is observed in the resonance frequency. For the low linear thermal expansion coefficient of the cavity metal and short measurement time (within 20 s), the effect of the room temperature variation is relatively small and thus not considered here.

The signal attenuation within the liquid sample at resonance is evaluated using the characteristic depth of penetration d_p, which is defined as the depth where the signal magnitude is reduced to $1/e$ (about 37%) of its original value and can be calculated by (Pozar, 2012):

$$d_p = \frac{c}{\sqrt{2}\pi f_2\left\{\varepsilon_r'\left[\sqrt{1 + \left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2} - 1\right]\right\}^{1/2}} \tag{4}$$

where c is the speed of light in free space.

Principal component analysis is employed here to extract the dominant features (principal components) from the signal magnitudes of each sample over the whole frequency range. By singular value decomposition, the number of the data dimensions can be significantly reduced and the features that contain the most relevant information can be obtained. The built-in MATLAB® function *pca* is used for fast computation. The scores generated are the representations of the raw data in the principal component space. The first two component (i.e., 1st and 2nd components) values of the scores are chosen for sample classification.

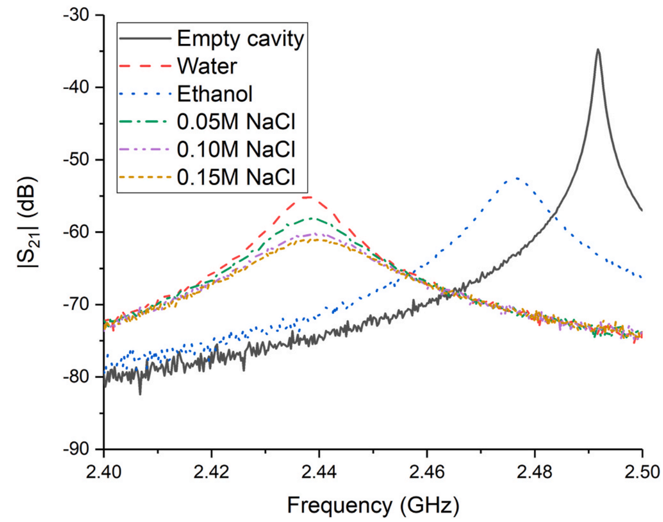

Fig. 3. Signal responses of the empty cavity and standard liquids.

2.3. Experimental setup

The photograph of the resonance measurement is shown in Fig. 2 (a). The cavity resonator was connected to a portable N9951A Fieldfox microwave analyser (Keysight Technologies, Santa Rosa, CA) by two coaxial cables (A-info Inc., Chengdu, China). The cables can be operated up to 18 GHz. A LAN cable was used to link the analyser to a personal computer. A MATLAB® graphical user interface (GUI) (shown in Fig. 2 (b)) was programmed to facilitate the data extraction and post-processing.

In the test, the NA (network analyser) mode of the analyser was chosen, and a frequency range of 2.4–2.5 GHz was set with 401 sampling points. The default signal power (i.e., 0.032 mW) was used, and the intermediate frequency bandwidth was set to 100 Hz to reduce the noise floor. Four repeated measurements were performed for each sample. No presence of any visible air bubbles in the liquid sample was checked by using a magnifying glass with 5 × magnification. From the accurate measurement of the standard liquids, the effectiveness of the examination was confirmed. No liquid leakage was seen as the cavity was positioned with the axis in the horizontal plane.

3. Results and discussion

3.1. Standard liquid samples

The resonant responses of the empty cavity and standard liquids are presented in Fig. 3 and Table 4. When a sample is inserted, the resonance frequency is shifted downwards, and the magnitude at the peak is reduced due to the energy absorption by the sample. For the empty cavity case, good agreement is found in the resonance frequency between the simulation and the test, where an error of 1% is achieved. The quality factor of the real cavity is smaller than the simulation value due to the leakage at the interfaces between the cylindrical wall and the endplates, surface roughness and the material used was not as pure as the material modelled. However, the discrepancy between the simulation and experiment is not regarded as significant, as reasonable

Table 4
Resonant parameters of the empty cavity and standard liquids.

	Empty cavity	Water	Ethanol	0.05M NaCl	0.10M NaCl	0.15M NaCl
Resonance frequency (f_r, GHz)	2.49175	2.43850	2.47619	2.43825 ± 0.00036	2.43875 ± 0.00120	2.43910 ± 0.00129
Quality factor (Q)	2004.36 ± 12.79	221.51 ± 7.06	267.07 ± 9.33	153.20 ± 5.30	121.28 ± 7.73	111.75 ± 9.20

Table 5
Permittivity of the standard liquid samples obtained from the resonance measurement.

	Water	Ethanol	0.05M NaCl	0.10M NaCl	0.15M NaCl
Reference data	76.99-j9.31 (Cole & Cole, 1941)	7.36-j7.12 (Petong, Pottel, & Kaatze, 2000)	76.12-j12.54 (Stogryn, 1971)	75.17-j16.16 (Stogryn, 1971)	74.23-j19.70 (Stogryn, 1971)
Present work	79.77 (±0.52)-j9.48 (±0.32)	7.56 (±0.53)-j7.72 (±0.15)	79.77 (±0.26)-j14.33 (±0.20)	78.98 (±0.90)-j18.42 (±0.47)	78.34 (±0.93)-j20.10 (±0.67)
Estimation error averaged ($\Delta\varepsilon_r^{'}/\|\varepsilon_r\|$, %)	3.58	1.92	4.73	4.95	5.35
Estimation error averaged ($\Delta\varepsilon_r^{''}/\|\varepsilon_r\|$, %)	0.22	5.89	2.33	2.94	0.52

permittivity results are offered by the quality factors measured. All the quality factors in the sample cases are one order of magnitude lower than that of the empty cavity. Between the repeated measurements of each sample, the resonance frequency hardly changes, while relatively small variations are seen in the quality factor. Permittivity values calculated are listed in Table 5. For a sample with a higher loss factor, the uncertainty (95% confidence interval) of the quality factor is relatively larger. Compared with the theoretical values found in the

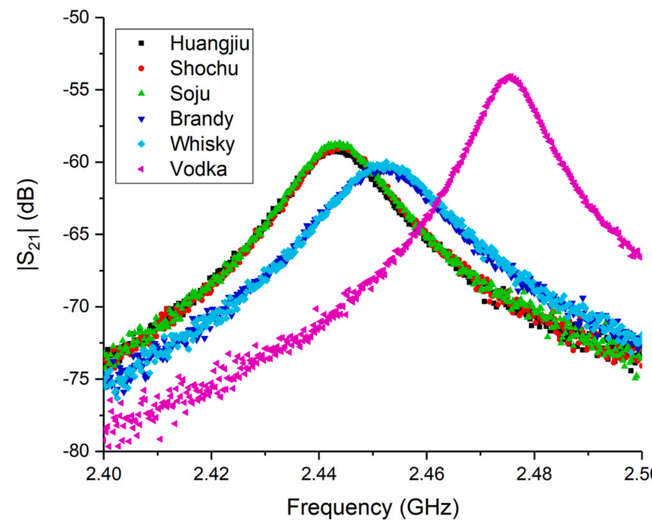

Fig. 5. Signal responses of six other alcohol samples.

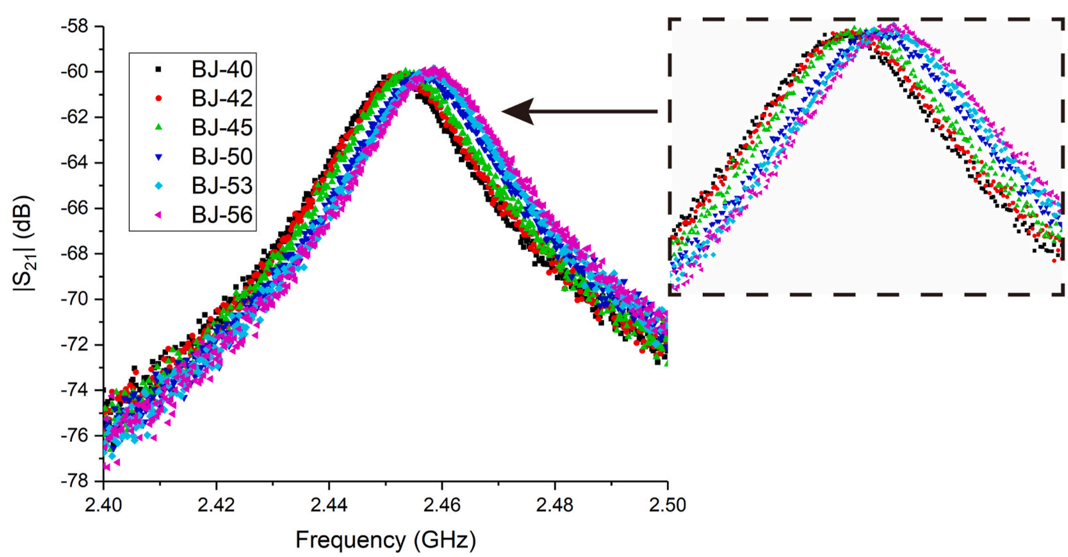

Fig. 4. Resonance curves of the baijiu samples.

Table 6
Resonant responses and permittivity values of the baijiu samples.

	BJ-40	BJ-42	BJ-45	BJ-50	BJ-53	BJ-56
f_r (GHz)	2.45238 ± 0.00124	2.45256 ± 0.00068	2.45413 ± 0.00140	2.45613 ± 0.00040	2.45794 ± 0.00105	2.45906 ± 0.00105
Q	119.15 ± 5.72	118.89 ± 6.22	119.44 ± 6.75	118.56 ± 6.19	125.81 ± 6.88	121.36 ± 5.53
$\varepsilon_r^{'}$	52.99 ± 1.15	52.64 ± 0.63	49.66 ± 1.30	45.84 ± 0.37	42.38 ± 0.97	40.24 ± 0.97
$\varepsilon_r^{''}$	18.78 ± 0.46	18.82 ± 0.51	18.73 ± 0.55	18.88 ± 0.50	17.73 ± 0.50	18.41 ± 0.44

Table 7
Resonant responses and permittivity values of six other alcohol samples.

	Huangjiu	Shochu	Soju	Brandy	Whisky	Vodka
f_r (GHz)	2.44350 ± 0.00210	2.44375 ± 0.00086	2.44331 ± 0.00050	2.45131 ± 0.00190	2.45269 ± 0.00143	2.47544 ± 0.00082
Q	138.94 ± 9.13	142.31 ± 8.93	146.79 ± 6.05	115.54 ± 5.10	120.60 ± 10.11	228.11 ± 4.25
$\varepsilon_r^{'}$	69.92 ± 1.95	69.44 ± 0.80	70.28 ± 0.46	55.02 ± 1.77	52.40 ± 1.33	9.01 ± 0.76
$\varepsilon_r^{''}$	15.95 ± 0.53	15.54 ± 0.49	15.02 ± 0.32	19.40 ± 0.44	18.56 ± 0.79	9.24 ± 0.09

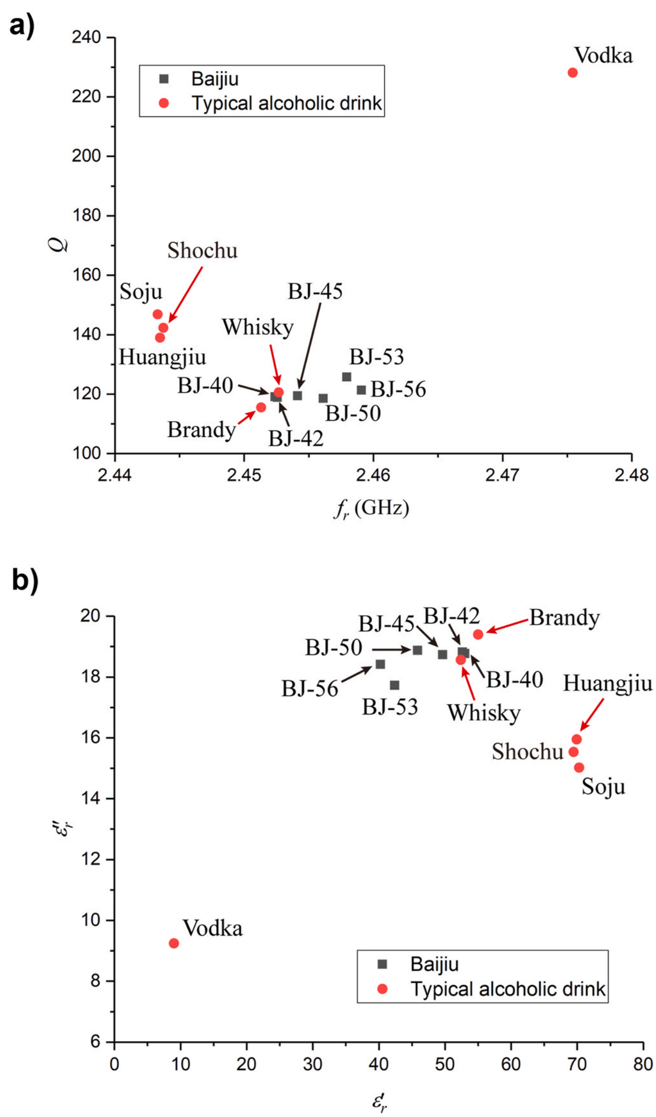

Fig. 6. Comparison of the resonant responses and dielectric properties of the baijiu and other alcohol samples: (a) f_r-Q diagram; (b) $\varepsilon_r^{'}$-$\varepsilon_r^{''}$ diagram.

literature, the measurement errors are well within ±6%. The results obtained are comparable to those offered by a commercial probe (Agilent probe) (i.e., ±5% for both $\Delta\varepsilon_r^{'}/|\varepsilon_r|$ and $\Delta\varepsilon_r^{''}/|\varepsilon_r|$ (Agilent Technologies, 2006)), showing satisfactory uncertainty values.

3.2. Baijiu samples

The frequency responses of the baijiu samples are shown in Fig. 4, where the resonance frequency is larger at a higher ABV. The resonant responses and permittivity of each baijiu sample are given in Table 6, where $\varepsilon_r^{'}$ decreases with increasing ABV. However, no substantial trend is found in $\varepsilon_r^{''}$. It is noted that the ratio of the uncertainty with respect to the mean value is the lowest in the resonance frequency among the four parameters of interest.

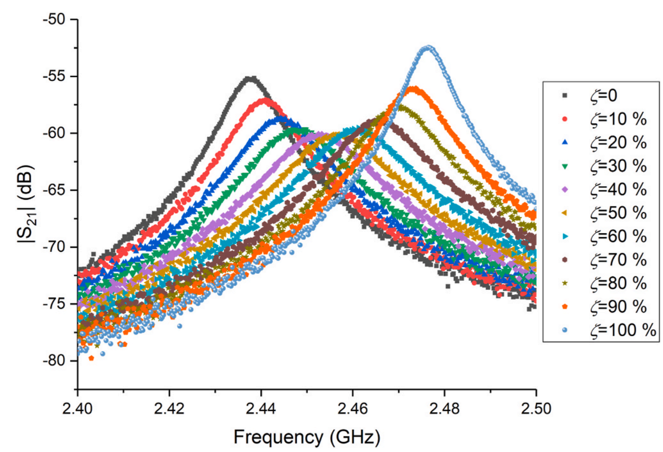

Fig. 7. Resonant responses of the ethanol-water mixtures.

3.3. Other typical alcoholic drinks

The signal responses of six other alcoholic drinks measured by the proposed method are shown in Fig. 5, where the curves of huangjiu, shochu and soju overlap due to similar ABV values. The resemblance is also seen in the curves of the brandy and whisky samples. The detailed experimental data are listed in Table 7 and Fig. 6. In the f_r-Q and $\varepsilon_r^{'}$-$\varepsilon_r^{''}$ plots, the dependence of the dielectric properties on the alcohol content is well demonstrated. For a sample with a higher ABV value, the resonance frequency is higher and $\varepsilon_r^{'}$ is lower. The points for the BJ-40 and whisky samples with the same ABV are adjacent. It is interesting to note that there are two exceptions, i.e., shochu and soju. Given the findings from the two plots, the ABV of soju should be lower than that of shochu, while the opposite is seen in Table 2. This would suggest some mislabelling about the ABV values reported, which is confirmed by the results presented and discussed in Section 3.4. In addition, it appears that the ABV of huangjiu is close to that of shochu.

4. Discussion

(1) *Diluted ethanol*: The resonance curves for the ethanol-water mixtures are presented in Fig. 7. The resonance frequency is shifted upwards when more ethanol is added into water, approaching the pure ethanol case as would be expected. The variations of the parameter values with respect to ABV are shown in Fig. 8. In terms of the resonance frequency (Fig. 8 (a)), the points are closely scattered around the line connecting the points of the two pure cases (i.e., pure water and ethanol), thereby satisfying the law of mixture. This linear trend is also found in the $\varepsilon_r^{'}$-ABV diagram (Fig. 8 (b)). In comparison, non-linear relations are seen in Q and $\varepsilon_r^{''}$. For each ethanol-water mixture, the ratio of r_1 to d_p is computed and the value is well below 5%, indicating that the whole volume of the sample can be fully interrogated by the sensor.

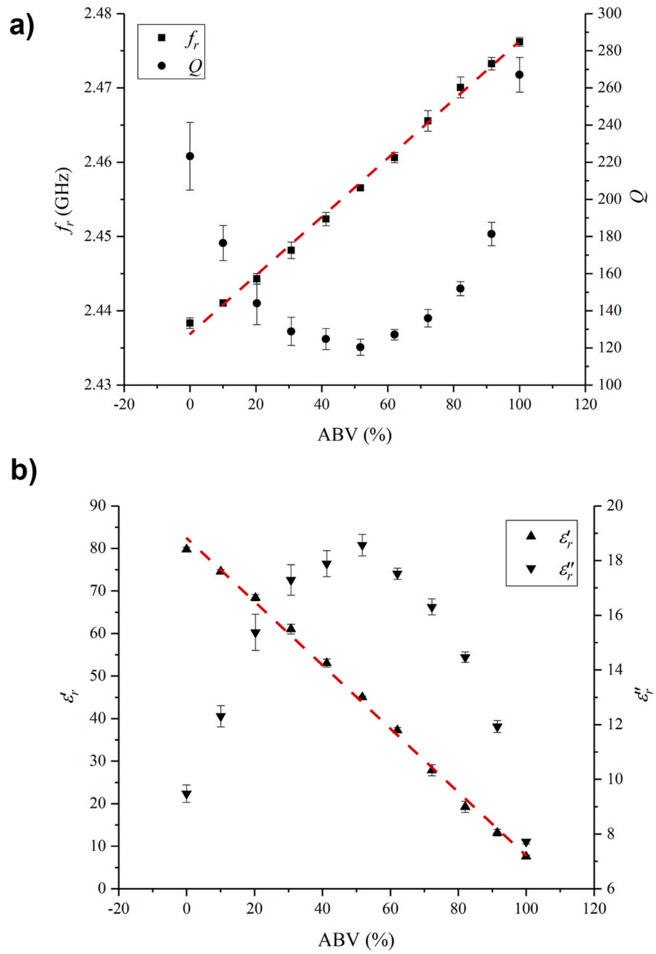

Fig. 8. Variations of the resonant parameters and dielectric properties of the ethanol-water mixtures with respect to ABV (error bars represent the deviations of four replicates): (a) f_r and Q; (b) ε_r' and.ε_r''

The regression analysis is introduced to reveal the relationships between f_r and ABV and between ε_r'' and ABV. The linear fits obtained are

$$f_r = 0.0393\text{ABV} + 2.4369 \tag{5a}$$

$$\varepsilon_r' = -74.9760\text{ABV} + 82.5710 \tag{5b}$$

The coefficients of determination in both Equations (5a) and (5b) are $R^2 = 0.99679$, indicating very good matching. R^2 is a common parameter in curve fitting that shows how well the fit function follows the trend in the data. When R^2 is equal to one, a perfect fit is achieved. Similar to the baijiu results, the uncertainty of the resonance frequency is the lowest. However, from the dynamic range point of view, Equation (5b) could provide better accuracy for ABV prediction. Considering the uncertainties of ε_r' (Tables 6 and 7), the average estimation accuracy of ABV is approximately $\pm 1\%$, which is comparable to that of a widely used hydrometer. It should be noted that a hydrometer measures the relative density of liquids based on buoyancy, and it can only be used for the specific alcoholic drink type that has been calibrated. Other methods like densitometry, near- and mid-infrared spectroscopy and gas chromatography can also be employed for the alcohol content determination, while the expensive equipment associated means that these techniques are more suitable for large companies and research laboratories. In comparison, the microwave method presented here has the potential of providing a universal and relatively economical solution with one scale for a wider range of alcohols.

Equation (5a) is applied to estimate the resonance frequencies of all the alcoholic drinks other than huangjiu, shochu and soju. The results are presented in Table 8, where all the errors are within 1%, indicating correct labelling in these drinks. Therefore, the resonance frequency of an alcoholic drink is linearly related to the alcohol content. By performing the inverse calculation, the ABV values of shochu and soju are 17.5% and 16.4%, respectively. Hence, the shochu product is more likely to be mislabelled.

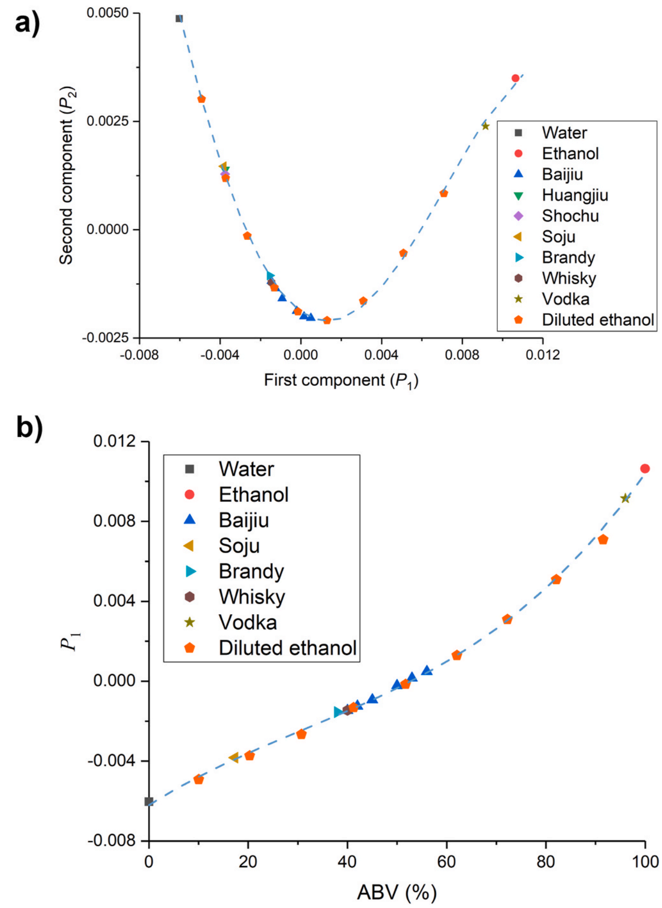

Fig. 9. PCA results from the resonant responses of all the samples measured: (a) score plot of the first component values versus the second component values; (b) variation of the first component value with respect to ABV.

(2) *Principal component analysis*: The score plot generated is shown in Fig. 9 (a), where pure water has the lowest first component (denoted by P_1) value and pure ethanol has the highest P_1 value, suggesting that P_1 value increases with increasing alcohol content. In terms of the second component (denoted by P_2), the diluted ethanol solution with $\zeta = 60\%$ (ABV of 62.06%) has the smallest value. It is noted that all the points can be perfectly fitted by a fourth-order polynomial with a high coefficient of determination ($R^2 = 0.9984$). The variation of P_1 with respect to ABV is also plotted and shown in Fig. 9 (b), where the points for the samples with similar ABV values are closely scattered. An alcoholic drink with an ABV value out of the baijiu range can be well differentiated from baijiu. Similarly, a third-order polynomial can well fit the points with $R^2 = 0.9985$. Hence, P_1 provided by PCA can be an alternative indicator for the evaluation of the alcohol content. The fitted curves in Fig. 9 (a) and (b) are expressed by

$$P_2 = -259140P_1^4 - 2270.3P_1^3 + 131.31P_1^2 - 0.3272P_1 - 0.0019 \tag{6a}$$

$$P_1 = 0.0176\text{ABV}^3 - 0.0166\text{ABV}^2 + 0.0156\text{ABV} - 0.0062 \tag{6b}$$

Table 8
Prediction of the resonance frequencies of the alcoholic drinks using the finding from the study of the ethanol-water mixtures.

	BJ-40	BJ-42	BJ-45	BJ-50	BJ-53	BJ-56	Brandy	Whisky	Vodka
f_r estimated (GHz)	2.4526	2.4534	2.4546	2.4566	2.4577	2.4589	2.4518	2.4526	2.4746
Error (%)	0.0100	0.0344	0.0187	0.0173	−0.0085	−0.0063	0.0213	−0.0028	−0.0327

The ABV of shochu calculated from Equation (6b) is 18.0%, which agrees well with the result from Equation (5b).

5. Concluding remarks

The dielectric properties of baijiu have been thoroughly investigated, where a low-cost microwave cylindrical cavity resonator sensor is developed for the extraction of the resonant responses and the complex electric permittivity. Six baijiu samples with varied ABV values from 40% to 56% were measured. It has been shown that the resonance frequency increases with increasing alcohol content, leading to decreasing ε_r'. The permittivity obtained here can provide useful references for microwave processing of baijiu-related products. Six other types of commercially available alcoholic beverages with ABV values from 15% to 96% were also tested and compared. It has been found that a sample with an alcohol content out of the baijiu ABV range has distinctive values of resonance frequency, quality factor, ε_r' and ε_r''. However, samples (e.g., whisky) with very similar alcohol contents to baijiu cannot be readily differentiated (though in practice they can be distinguished by colour/aroma). In addition, the effect of the ethanol content on the dielectric characteristic has been studied with ethanol-water mixtures. The variations of the resonance frequency and ε_r' conform to the law of mixture and linear relationships are established. The real part of the permittivity is preferred for the estimation of the alcohol content of an alcoholic drink. From the assessment of the penetration depths, it is shown that volumetric penetration can be achieved. The principal component analysis has also been employed. Interestingly, the relationship between the first and second component values of all the liquids tested perfectly satisfies a fourth-order polynomial function, and the alcohol content can also be computed from the first component value.

It has been demonstrated that the microwave method presented has the potential in the ABV determination for a wide range of alcoholic drinks including baijiu. The distinctive advantages of the present work are the need for only a very small volume of liquid (less than 0.1 mL), easy operation and broad applicability. Future work will be conducted to investigate the temperature effect on the permittivity of baijiu. Further development could reduce the cost of the whole measuring system, such as bespoke design of a microwave source with a shorter frequency bandwidth that would be sufficient for the measurements reported.

CRediT authorship contribution statement

Zhen Li: Investigation, Formal analysis, Writing - original draft. **Arthur Haigh:** Conceptualization, Methodology. **Ping Wang:** Writing - review & editing, Supervision. **Constantinos Soutis:** Writing - review & editing, Supervision. **Andrew Gibson:** Methodology, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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