

Experimental Study on a Simple-Structured Microwave Sensor for ABV Determination in Alcoholic Beverages

Jirarat Sornprasert, Nutdechatorn Puangngernmak*, and Prayut Jiamrittivong

Department of Energy Technology and Management, Faculty of Energy and Environmental Sciences,
King Mongkut's University of Technology North Bangkok
Corresponding author: nutdechatorn.p@sciee.kmutnb.ac.th*

Abstract

Alcohol by Volume (ABV) is a standard measure of alcohol content in beverages. For quality control in community-level enterprises, accurate and real-time ABV assessment is crucial. However, traditional tools like hydrometers are destructive and cannot provide real-time analysis. This research introduces a microwave sensor-based technique that measures the reflection coefficient (S_{11}), which is directly influenced by the liquid's complex relative permittivity. A comparative study was conducted using ethanol solutions of known concentrations, distilled water, and commercial alcoholic beverages. Our findings show that the complex relative permittivity and S_{11} values of commercial alcoholic beverages closely match those of corresponding ethanol solutions. For instance, 40% ABV beverages exhibited values similar to 40% ethanol samples, while 35% ABV beverages were comparable to 35% to 40% ethanol samples, and 13% ABV beverages aligned with 10%-20% ethanol samples. This innovative approach offers a promising, real-time, and non-destructive solution for ethanol content verification in community enterprise settings.

Keywords: Permittivity, Microwave sensor, Alcohol by Volume (ABV)

1. Introduction

Accurate Alcohol by Volume (ABV) determination is crucial for quality control and regulatory compliance in the alcoholic beverage industry. Ensuring consistent ethanol content is vital for product quality, consumer safety, brand reputation, and adherence to standards, especially for community-level enterprises benefiting from efficient quality assessment [1].

Many community enterprises in Thailand currently rely on conventional hydrometers for ABV verification. Despite their simplicity, these tools have significant limitations for modern production. They are destructive, requiring batch sampling, and lack real-time or in-line analysis, hindering continuous monitoring. Furthermore, their accuracy is compromised by other dissolved solids, such as sugars, which independently alter liquid density, leading to inaccurate readings. These drawbacks highlight a clear need for advanced, non-destructive, and real-time analytical solutions [2]-[5].

Microwave sensors operate by measuring a substance's dielectric properties, which are fundamentally influenced

by its molecular composition. The distinct molecular polarities and relaxation times of ethanol and water create unique dielectric responses at microwave frequencies, enabling precise and rapid determination of ethanol concentration in aqueous solutions. Thus, microwave sensing offers a promising avenue for developing non-invasive, rapid, and potentially in-line ABV verification methods [6]-[8].

This study investigates the feasibility and performance of a simple-structured microwave sensor for accurate Alcohol by Volume (ABV) detection in alcoholic beverages. The research aims to develop a cost-effective microwave sensor for real-time ABV measurement, characterize the complex relative permittivity and reflection coefficient (S_{11}) of various ethanol-water mixtures across a range of microwave frequencies, and compare the measurement results of commercial alcoholic beverages with those of known ethanol solutions to validate the sensor's applicability. This work aligns with the theme of "Intelligent technology and innovation for human sustainability" by offering a practical solution for quality control in community enterprises [2]-[3],[9]-[12].

2. Experimental Setup and Simple-Structured Microwave Sensor

The proposed microwave sensor utilizes a simple coaxial probe structure designed to sense the dielectric properties of the liquid under test (LUT) [13]. The sensor used is made from brass shown in Figure 1, the sensor operates by placing the LUT in contact with the probe, allowing electromagnetic waves to interact with the sample.

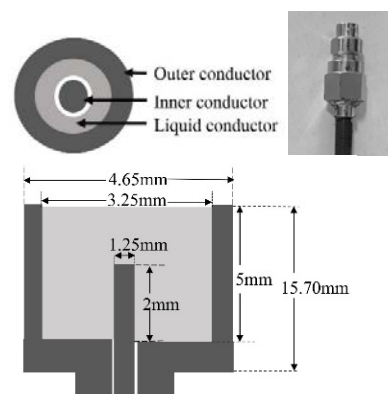


Fig. 1 Simple-Structured Microwave Sensor

*Corresponding Author

A Vector Network Analyzer (VNA) then measures changes in the reflection coefficient (S_{11}) at the sensor-liquid interface, which directly relate to the liquid's complex relative permittivity (ϵ_r).

Complex relative permittivity is defined as

$$\epsilon_r = \epsilon' - j\epsilon'' \quad (1)$$

where ϵ' is the real part, representing the material's ability to store electrical energy (dielectric constant), and ϵ'' is the imaginary part, representing energy loss (dielectric loss factor). Both are frequency-dependent and sensitive to molecular composition and temperature. For water-ethanol mixtures, the significant difference in dipole moments and relaxation times between water and ethanol molecules causes distinct changes in ϵ' and ϵ'' with varying concentration [2].

From the equivalent circuit (Figure 2), the relationship between the reflection coefficient and complex permittivity is:

$$S_{11} = \Gamma^* = \Gamma e^{j\phi} = \frac{1 - j\omega Z_0 [C(\epsilon_r) + C_f]}{1 + j\omega Z_0 [C(\epsilon_r) + C_f]} \quad (2)$$

Here, S_{11} is a reflection coefficient, Z_0 is the measurement system's impedance, $C(\epsilon_r)$ is the coaxial structure's capacitance, which is dependent on the permittivity of the LUT, and C_f is the air-induced stray field capacitance, independent of the LUT. The unknown parameters of the circuit model are determined by measuring the sensor with a standard liquid of known dielectric permittivity, such as distilled water.

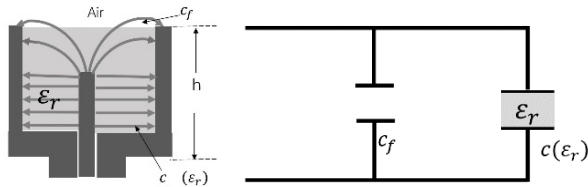


Fig 2. The equivalent circuit of a simple-structured microwave sensor

The experimental setup for measuring complex relative permittivity and S_{11} is shown in Figure 3. A KEYSIGHT N1501A Dielectric Probe Kit and Simple-Structured Microwave Sensor were connected to a Vector Network Analyzer (VNA) by 50 ohm cable (N9927-60017) for measurements conducted over a frequency range from 0.5 GHz to 18 GHz. To ensure consistency and accuracy, all liquid samples were maintained at a controlled temperature of 25°C using a water bath.

The liquids under test (LUT) included:

- Ethanol-water solutions: Prepared by mixing absolute ethanol (99.9% purity) with distilled water to achieve concentrations ranging from 0% (pure distilled water) to 100% (pure ethanol) by volume.
- Commercial alcoholic beverages: A variety of alcoholic beverages with known ABV percentages (e.g., 13%, 35%, 40%) were used to validate the sensor's performance in real-world scenarios.

Each measurement was repeated multiple times to ensure reproducibility, and the average values were used for analysis.

3. Result and Discussion

3.1 Dielectric Spectra of Pure Water and Ethanol

The complex relative permittivity (ϵ' and ϵ'') of pure water and 98.8% ethanol, measured from 0.5 GHz to 18 GHz, are shown in Figures 3 and 4. As shown in Figure 3, pure water's real permittivity ($\epsilon' \approx 80$ at 25°C) is significantly higher than that of ethanol ($\epsilon' \approx 24$ at 25°C) at microwave frequencies. This disparity is attributed to water's stronger molecular polarity and extensive hydrogen bonding, which enables greater electrical energy storage. Figure 4 illustrates the distinct imaginary permittivity (ϵ'') (dielectric loss) for both components, which exhibits more intricate behavior due to various relaxation phenomena. These fundamental dielectric differences between pure water and pure ethanol are crucial for differentiating ethanol concentrations within their mixtures. As the proportion of water and ethanol changes, the complex relative permittivity of the mixed solution changes accordingly because of the dipole-moment of LUT is changed.

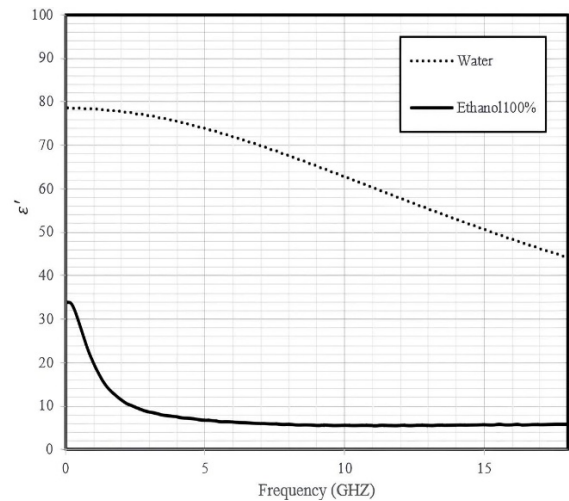


Fig. 3 Real parts of dielectric spectra of water-ethanol

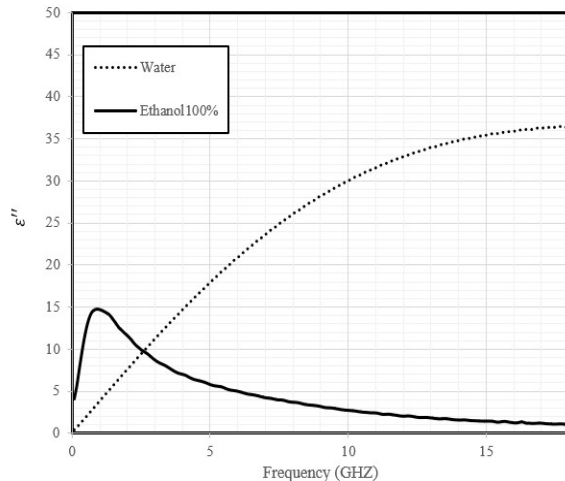


Fig. 4 Imaginary parts of dielectric spectra of water-ethanol

3.2 Reflection Coefficient (S_{11}) analysis of Ethanol

The reflection coefficient (S_{11}) of ethanol solutions at various concentrations are shown in Figure 5 and 6. A consistent trend was observed: increasing ethanol concentration generally led to a decrease in S_{11} magnitude, particularly within specific frequency ranges. This indicates that higher ethanol content results in greater microwave energy absorption or transmission into the liquid, thus reducing reflection. Concurrently, characteristic shifts in the S_{11} phase with concentration provided additional insights into the solutions' dielectric properties. The water-ethanol ratio affects the dipole moment of liquid that changing the dielectric constant as permittivity values.

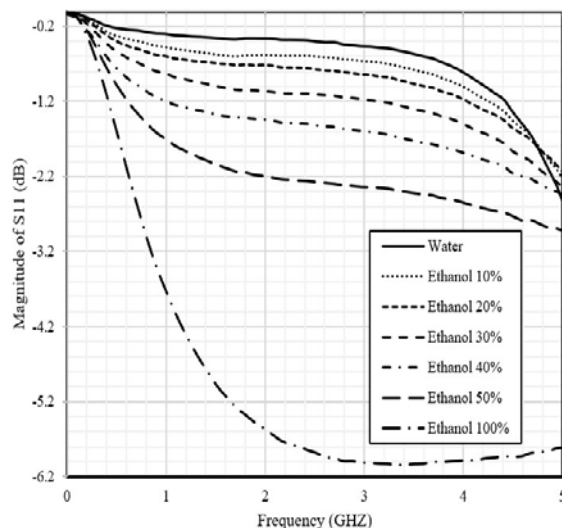


Fig. 5 S_{11} of water-ethanol solutions (0.3 GHz - 5 GHz)

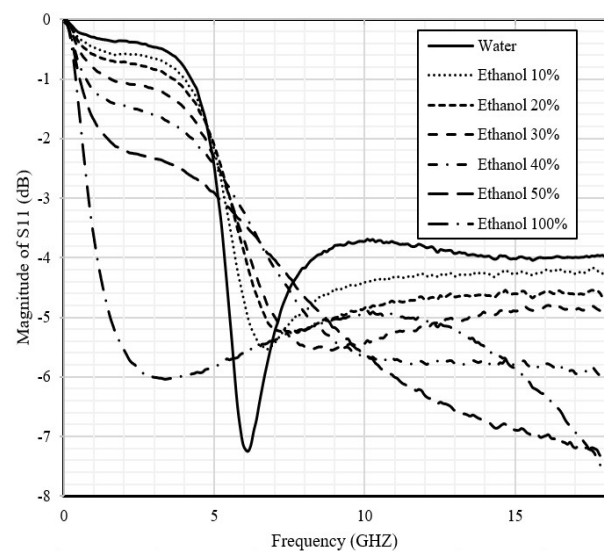


Fig. 6 S_{11} of water-ethanol solutions (0.3 GHz - 8 GHz)

However, above approximately 5 GHz, S_{11} values oscillatory behavior, complicating precise interpretation. This phenomenon likely arises from impedance mismatch between the sensor and VNA or from the excitation of higher-order modes within the coaxial structure, which can interfere with accurate measurements. Consequently, further optimization of sensor design and calibration procedures, especially for higher frequency ranges, is necessary to mitigate this effect.

3.3 Comparison of Alcoholic Beverages with Water-Ethanol Solutions

The magnitude of S_{11} for various commercial alcoholic beverages compared to those of ethanol solutions with corresponding ABV percentages are shown in Figure 7 and 8. The results indicate that alcoholic beverages with 40% ABV of **White Spirit** exhibit S_{11} values that are remarkably similar to those of 40% ethanol solutions. Similarly, beverages with 35% ABV of **Whisky Cast** show comparable values to 35% to 40% ethanol samples, and those with 13% ABV of **Soju (Fruit Wine)** align well with 10% to 20% ethanol samples. This strong correlation suggests that the microwave sensor can effectively determine the ABV of real-world alcoholic beverages, despite the presence of other components like sugars, flavors, and colorants. This indicates that the dielectric properties of water and ethanol are the dominant factors influencing the microwave response in these beverages.

The oscillatory behavior observed at higher frequencies was also present when testing commercial alcoholic beverages, reaffirming the need for sensor and measurement setup optimization for robust performance across the entire frequency spectrum. Despite this, the consistent correlation at lower frequencies demonstrates

the significant potential of this simple-structured microwave sensor for practical ABV verification.

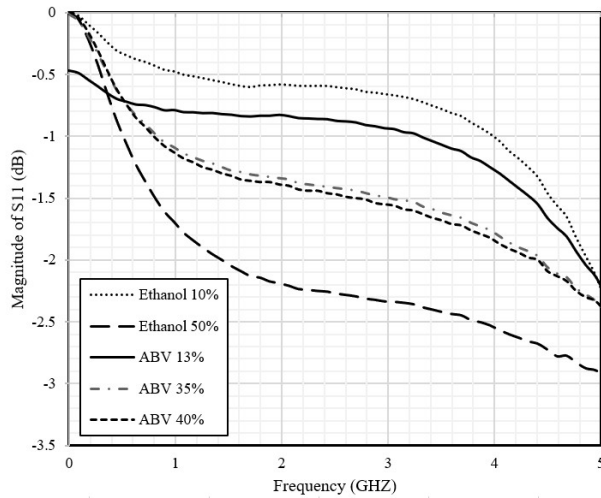


Fig. 7 S_{11} of difference in concentration of water-ethanol and alcoholic drink (0.3 GHz - 5 GHz)

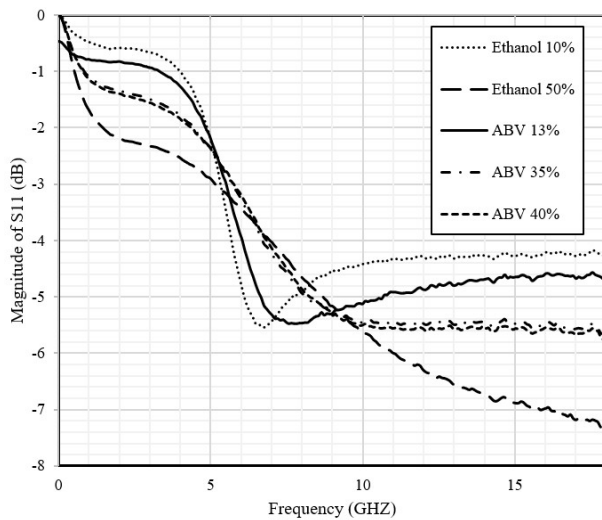


Fig. 8 S_{11} of difference in concentration of water-ethanol and alcoholic drink (0.3 GHz - 18 GHz)

4. Conclusions

This research successfully demonstrated the feasibility of using a simple-structured microwave sensor for real-time, non-destructive detection of Alcohol by Volume (ABV) in alcoholic beverages. The study established a clear correlation between the complex relative permittivity and reflection coefficient (S_{11}) of ethanol-water mixtures and their respective ethanol concentrations.

Key findings are as follows: The real part of permittivity (ϵ') significantly decreases with increasing ethanol concentration, while the imaginary part (ϵ'') also shows distinct changes, enabling differentiation of mixtures. The reflection coefficient (S_{11}) varied

effectively with ethanol concentration, providing a reliable parameter for measurement. Furthermore, commercial alcoholic beverages exhibited dielectric properties and S_{11} values that closely matched those of pure ethanol solutions at corresponding ABV levels, validating the sensor's applicability in real-world scenarios.

Table 1 Magnitude of S_{11} of Ethanol Concentration

%Ethanol Concentration	Magnitude of S_{11} (dB)		
	2GHz	3GHz	4GHz
Ethanol 0%	-0.361	-0.468	-0.850
Ethanol 10%	-0.585	-0.669	-1.040
Ethanol 20%	-0.724	-0.849	-1.210
Ethanol 30%	-1.075	-1.189	-1.533
Ethanol 40%	-1.455	-1.608	-1.909
Ethanol 50%	-2.207	-2.337	-2.566
Ethanol 100%	-5.633	-6.015	-5.978

Table 2 Magnitude of S_{11} of Ethanol Concentration and Alcohol by Volume in Alcoholic Beverages

%Ethanol Concentration	Magnitude of S_{11} (dB)		
	2GHz	3GHz	4GHz
Ethanol 10%	-0.585	-0.669	-1.040
Ethanol 50%	-2.207	-2.337	-2.566
ABV 13%	-0.837	-0.942	-1.300
ABV 35%	-1.350	-1.510	-1.810
ABV 40%	-1.400	-1.560	-1.870

The S_{11} values for ethanol solutions in the 2 GHz - 4 GHz frequency band tend to decrease as frequency increases. This trend is consistent with the solutions' electrical properties, which demonstrate an attenuation of electromagnetic energy in the high-frequency region, as shown in **Table 1**.

When these experimental results are compared with those of alcoholic beverages, as presented in **Table 2**, the S_{11} values for the studied beverages fall within the range of ethanol solutions with concentrations of 10% to 50% by volume. This finding aligns with the alcohol by volume (ABV) values listed on the labels of these beverages.

This innovative approach offers a promising solution for enhancing quality control in community enterprise settings, providing a rapid, non-destructive alternative to traditional methods like hydrometers. The technology aligns well with the theme of "Intelligent technology and innovation for human sustainability" by promoting efficient and sustainable production practices.

For future work, further optimization of the sensor design is recommended to mitigate the "swing" value observed at higher frequencies, ensuring more stable and accurate measurements across a wider spectrum. Additionally, expanding the study to include a broader range of alcoholic beverages with diverse compositions and conducting long-term stability tests would further validate the sensor's robustness for practical deployment. The ultimate goal is to develop a compact, portable, and user-friendly prototype for direct implementation in community production lines.



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