Detection of Ethanol Concentration in Liquid Using a Double-Layered Resonator Operating at 5G-mm-Wave Frequencies

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Abstract
A new sensing technique for rapidly detecting ethanol concentration in aqueous solutions based on electromagnetic resonance is discussed. The sensor has two substrate layers and operates at 5G-mm-wave frequencies. An experimental study of the new resonator’s configuration determines the sensor’s sensitivity. During the measurements, 6 samples were modeled with varying amounts of ethanol concentration in the water. The results showed that $S_{11}$ resonance moves linearly towards higher frequencies as the ethanol content increases. The resonant frequency shifted at 0.178 GHz per 10% increase in ethanol towards higher frequencies. As a result, the proposed 5G-mm-wave-sensing technique based on a replaceable sensing layer was proved to be suitable for rapid, accurate, and low-cost alcohol content detection in liquids.

Keywords Resonator · 5G-mm-wave · Ethanol · Liquid · Sensor

Introduction
The amount of the ethanol content in alcoholic beverages is critical for quality control during their manufacturing process. Specific regulatory guidelines must be followed during the final stages of the brewing process of alcoholic beverages, which can be costly in developing countries, where consumers demand goods at reduced prices. Under such circumstances, merchants can illegally add ethanol to the beverage over an acceptable proportion to lower its price. According to one study, the ethanol content of red wine can range between 8% and 15% by volume. However, drinking alcohol with a high ethanol content can produce formic acid, which can cause various health problems, including fatigue, vertigo, blurred vision, vomiting, and death. As a result, developing a mechanism for monitoring ethanol content in these beverages using rapid testing is necessary to avoid potential health risks.

Traditional methods based on optical refraction are employed in laboratory testing to determine the quality of alcohol. However, the sugar content has an unavoidable effect on the measurements, and a hydrometer is often necessary during an investigation to determine the specific gravity of a liquid. Two advanced optical techniques, i.e., Raman spectroscopy and infrared wavelengths, are recommended to improve the accuracy of the measurements. However, measurements based on these optical techniques are susceptible to carbonation and fluorescence. Additionally, it is difficult to disentangle the contributions of ethanol and sugar from the spectral signature. Numerous approaches and techniques are used to fabricate viable, affordable, and portable sensors. Microwave sensors are more advanced than traditional sensing methods in the chemical and biomedical fields, as they provide robustness and high sensitivity.

In general, resonators used in sensing or measuring equipment provide precise measurements of the electromagnetic properties of any material at microwave frequencies. For low-loss materials, the resonant method provides accurate measurements. Resonators are well known for their compact size and sharp reflection/transmission coefficient representation, which results in enhanced performance. Additionally, this enables them to be used as instruments for measuring various physical parameters dependent on the permittivity

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or permeability of the sample. According to the measured physical parameters, microwave resonators are configured to produce a relative resonant frequency and/or oscillating phase response.

A resonator sensor has been demonstrated for ethanol, methanol, and isopropyl alcohol (IPA) applications. Moreover, resonating structures incorporating transmission lines have been reported for use in various sensory applications. In a contactless sensor operating at 2.4 GHz characterizing liquids, the material under test was inserted inside a capillary tube parallel to the sensor’s surface, and the shift in transmission coefficient ($S_{21}$) was observed. The analysis was conducted by establishing a reference sample and correlating it to other samples. The same phenomenon, where a pair of split-ring resonators were used to identify various loads using the transmission coefficient as the primary sensing parameter, has also been demonstrated, while an omega-shaped resonator coupled to a microstrip transmission line has been proposed for analyzing changes in Q-factor and $S_{21}$ as a function of chemical content variation in liquids.

Additionally, measurements in the frequency range of 2.5–3 GHz were made on ethanol and methanol mixtures with pure water. Another transmission line sensor for characterizing methanol has been proposed. The measurements were taken between frequencies of 6 GHz and 8 GHz. The resonant frequency shift was observed up to 0.15 GHz as the methanol content increased from 0% to 100%. However, to the best of the author’s knowledge, no resonator for the characterization of alcohol liquids operating at higher frequencies, such as 5G-mm-wave frequencies, has been proposed. It is worth noting that liquids with high water content, such as alcohol and other aqueous solutions, are dispersive media with frequency-dependent electromagnetic properties. The mm-wave frequency range is well suited for alcohol sensing because it increases sensitivity to the analyte sample’s dielectric constant and loss tangent. Additionally, switching from lower microwave frequencies to this frequency results in a reduction in the size of the resonating structure. The resonator design was fabricated by transforming the analytical model of CST into the physical structure. The fabricated design is shown in Fig. 2, connected by two 2.4-mm reusable SMA connectors. The magnitude of the reflection coefficient of the sensor design can be mathematically defined by Eq. (1):

$$S_{11} = 20 \log \left| \frac{Z_m - Z_0}{Z_n - Z_0} \right|$$

where $Z_m$ is the input impedance realized at P1, while $Z_0$ is the characteristic impedance of the transmission line on the bottom substrate layer. $Z_n$, on the other hand, is defined by Eq. (2):

$$Z_n(\omega, \varepsilon_{\text{eff}}) = j\omega L + j\omega^2 C_{\text{eff}}$$

Resonators typically have a resonance that can be electrically modeled using the lumped elements, $C_{\text{eff}}, L_{\text{eff}},$ and $R$. $L_{\text{eff}}$ is the resonating structure’s equivalent inductance. The equivalent circuit of the designed resonator is depicted in Fig. 3. The inductance of the design consists of two parts: (1) mutual inductance between triangular resonators ($M$), and (2) mutual inductance between two strip lines ($M'$). $C_{\text{eff}}$ is defined as the equivalent capacitance of the entire
structure, including the capacitances produced between the triangular resonators and the adjacent strip lines. Adding the triangular resonators between the two slots increases the effective capacitance, which improves the interaction between the resonating structure and the sample.

Modifying the sample within the sensor’s proximity will change the sensor’s effective permittivity. Consequently, variation in effective permittivity, $\varepsilon_{\text{eff}}$, will change the overall capacitance, $C_s$, thereby changing the input impedance realised at P1. The effective resistance is defined by $R$, which depends on the conductivity of copper material and the

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**Table 1** Optimized dimensions of sensor.

| Dimension | Value (mm) |
|-----------|------------|
| $L_2$     | 6.0        |
| $T_0$     | 3.1        |
| $W$       | 0.6        |
| $L_1$     | 4.60       |

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**Fig. 1** Sensor design: (a) transmission line on the bottom layer, (b) resonator structure on the top layer, (c) side view of the integrated top and bottom layers, and (d) 3D view.

**Fig. 2** Fabricated design of the sensor.

**Fig. 3** Equivalent circuit of the resonator.

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sample. \( \omega_0 \) represents the resonant frequency of the structure. This model aims to demonstrate the implicit relationship between the reflection coefficient and the sensor’s sensing mechanism. This relationship helped to understand the effect of permittivity change in the sample in the subsequent portions of this study.

**Results and Analysis**

**Resonant Frequency**

The comparison of the simulated and measured reflection coefficient \( (S_{11}) \) behavior is shown in Fig. 4, where the design is found to be resonating at 27.575 GHz with a negative amplitude of 47 dB. This confirms that the simulated and measured results are in good agreement at the resonant frequency. However, slight variations in amplitude can occur due to environmental parameters and imperfect fabrication.

**Sample’s Permittivity Analysis**

The effective permittivity and tangent loss of samples should be known to determine the sensor’s performance. Therefore, it was essential to determine the complex dielectric permittivity of the liquid under test (LUT) used during measurements in the sensor’s operating frequency range. The dispersive permittivity characteristics of the samples in complex form can be expressed using Eq. (3):

\[
\varepsilon(f) = \varepsilon' + j\varepsilon''(f)
\]

where \( \varepsilon' \) is the real permittivity, \( \varepsilon'' \) is the imaginary permittivity, while \( f \) is the frequency that defines the dispersive characteristics over the operating range of frequencies (20–35 GHz). The instantaneous permittivity over the operating frequency range is measured because materials’ permittivity exhibit a frequency dispersive phenomenon at high frequencies.\(^{19}\) The electromagnetic response of microwaves to water is considered a good starting point for developing a sensor because water is major content in alcohol.\(^{24}\) In this study, we chose ethanol as the LUT that is divided into 6 values of concentration ranging from 0% to 90%, obtained by adding 0, 17.5 mL, 22.5 mL, 35 mL, 40 mL, and 45 mL ethanol into 50 mL, 32.5 mL, 27.5 mL, 15 mL, 10 mL, and 5 mL of water, respectively. According to extensive research, water has a higher permittivity than alcohol.\(^{25,26}\) The permittivity of the LUTs was measured using a Keysight 85070E Dielectric Probe Kit. The measured permittivity of the samples can be expressed in terms of the fitted Debye parameters, as defined by Eq. (4):

\[
\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau}
\]

where \( \varepsilon_\infty \) is the dielectric constant at high frequencies, \( \varepsilon_s \) is the dielectric constant at low frequencies, and \( \tau \) is the relaxation time constant. The fitted parameters of the Debye model for each sample used in measurements are given in Table II.

**Simulation Analysis of Ethanol with Different Concentrations**

During the simulations, the LUTs were modeled by loading the permittivity values obtained in "Resonant Frequency" section. As illustrated in Fig. 5, the LUT was loaded across the sensor’s surface, completely covering the resonator structure. Each sample's resonant frequency was determined by substituting its dielectric properties. The resonance in transmission parameter, \( S_{21} \), or reflection parameter, \( S_{11} \), is typically considered for sensing purposes. Notably, the proposed design in this study had a negative peak in \( S_{11} \), which is consistent with previously described sensors with \( S_{11} \) as the sensing parameter.\(^{12,23,27,28}\) Figure 6 illustrates the simulated resonant frequencies for various ethanol concentrations. The resonant frequencies of samples at concentrations of 90%, 80%, 70%, 45.5%, 35.5%, and 0% are 27.06 GHz, 26.98 GHz, 26.9 GHz, 26.68 GHz, 26.58 GHz, and 26.34 GHz, respectively.

![Fig. 4 The resonant frequency of the sensor.](image)

![Table II Composition of liquid samples.](table)

| Ethanol (%) | 90  | 80  | 70  | 45  | 35  | 0   |
|------------|-----|-----|-----|-----|-----|-----|
| \( \varepsilon_\infty \) | 1.44 | 1.5 | 1.62| 1.85| 2.29| 7.73|
| \( \varepsilon_s \) | 10.85| 24.2| 44.05| 61.51| 71.17| 78.36|
| \( \tau \) (ps) | 22.5 | 33.86| 47.8 | 32.85| 24.45| 8.92|
It has been demonstrated that the resonant frequency moves toward higher frequencies with increased ethanol concentration. It is worth noting that the difference between the first and second data points (0% and 35% ethanol) is more significant than the difference between the other intervals due to the significant difference in their permittivity levels as defined by the Debye parameters in Table II. This introduces a small amount of non-linearity into the intervals, as the difference in resonant frequencies between samples containing 70% and 80% ethanol and samples containing 80% and 90% ethanol is only 0.08 GHz.

The linear regression analysis was also used to determine the sensor’s resonance shift in response to changes in ethanol concentration. This application establishes a relationship between the input (ethanol concentration) and the output (resonant frequency). After establishing a functional relationship between these two variables using training data on the obtained results, the relationship is validated using the same linear regression method on data that were not used during training. Thus, the validated model can forecast the output for which the data input is unknown. The regression analysis output applied to the resonance shift is shown in Fig. 6, where \( R^2 \) is the coefficient of determination, which indicates the degree to which the model fits accurately. It has a value between 0 and 1 and indicates the number of data points on the regression line. The obtained \( R^2 \) value of 0.9966 indicates that a significant proportion of data points lie on the regression line, implying that unknown outputs can be predicted with reasonable accuracy.

**Experimental Analysis of Ethanol with Different Concentrations**

During the measurements, coaxial cables of the N5234B PNA-L vector network analyzer (VNA) were connected to the sensor’s transmission lines via 2.4-mm reusable SMA connectors, as shown in Fig. 7. Before performing the measurements, the VNA was calibrated in three stages in the desired frequency range (20–35 GHz): open circuit, short circuit, and 50Ω loads. The six liquid samples listed in Table II were prepared with ethanol concentrations ranging from 0% to 90% to avoid unnecessary complexity. A dropper was used to insert liquid over the sensor’s surface, covering the entire resonator structure. The shift in resonance caused by increasing ethanol concentration.
concentration in the liquid sample is depicted in Fig. 8. Understandably, as the concentration of ethanol increases, the resonant frequency increases, which is consistent with the simulated results. The resonant frequencies for samples containing 90% ethanol and 0% ethanol are 27.05 GHz and 25.55 GHz, respectively, while the resonant frequencies for samples containing 80%, 45%, 35%, and 0% ethanol are 26.68 GHz, 26.6 GHz, 26.3 GHz, and 26.15 GHz, respectively. When applying regression analysis to the data points, measured results show a coefficient of determination of $R^2 = 0.978$, slightly less than the simulated result. The obtained coefficient of determination is still significant, implying that the higher percentage of data points lie on the regression line.

The electric energy stored at the resonance frequency must equal the magnetic field stored in the resonating structure. The presence of an external field influences the net electric and magnetic fields, consequently causing a disturbance in the resonance. Equation 5 can be used to get insight into the variation in dielectric properties of the external disturbances by associating the permittivity and permeability of the external medium with the resonant frequency’s perturbation. Perturbation is the phenomenon of realizing change in quality factor and/or shift in resonant frequency.

$$\frac{\Delta f_r}{f_r} = \frac{\int_0^\nu \left( \Delta \varepsilon E_0 E_1 + \Delta \mu H_0 H_1 \right) dv}{\int_0^\nu \left( \varepsilon_0 |E_0|^2 + |H_0|^2 \mu_0 \right) dv}$$

where $\nu$ represents the volume of external medium that is the volume of a sample that interacts with the electromagnetic fields of the structure, $E_0$ and $H_0$ are electric field distributions and magnetic field distributions without external distributions, respectively, $\varepsilon_0$ and $\mu_0$ are permittivity and permeability of free space, respectively, the change in the resonance (quality factor and/or shift) is represented by $\Delta f_r$, the change in net permittivity and permeability with an external medium is represented by $\Delta \varepsilon$ and $\Delta \mu$, respectively, and $E_1$ represents the external fields’ electric field distributions and $H_1$ represents external fields’ magnetic field distribution.

As stated in “Design and Fabrication of the Sensor” section, the external medium’s permittivity adds to the effective capacitance ($C_{eq}$) from one side of transmission line to the other side and its permeability adds to the induced current in the resonant element. Thus, it is reaffirmed that the permittivity of the introduced medium strongly influences the resonator structure on the top layer. Since the original fields have incorporated the aqueous solutions used in this work, it cannot be expected that the resonator’s internal field patterns will be approximately equal to the resonator’s field patterns without samples. This is because the interval field patterns show complicated field distributions after the sample placement. Even though the accurate prediction of the relationship is not possible, resonance shift can be realized versus ethanol’s concentration by a change in their permittivity values. From Eq. (6), the relative perturbation in the reflection coefficient can be approximated as:

$$\frac{\Delta f_r}{f_r} \approx \frac{-|\Delta \varepsilon| h}{2|\varepsilon| L}$$

where $\Delta \varepsilon$ is the difference in the permittivity of two consecutive ethanol concentrations as listed in Table II, $f_r$ is the reference resonant frequency, $\Delta f_r$ is the difference between reference and next resonant frequency, $h$ is the height of the sample’s drop introduced on the sensor’s surface, and $L$ is the length of the sample’s drop.

According to the measured results, the average $\Delta f_r$ for 10% change in ethanol’s concentration is determined as 0.178. The average length and the height of drop introduced on the sensor’s surface covering the resonator structure were 8 mm and 1 mm, respectively. Thus, the calculated average $\Delta f_r$ using Eq. (6) per 10% change in ethanol’s concentration, 0.146 is comparatively in agreement with measured results, which validates the application of the proposed geometry.

### Discussion

The simulation results showed a total resonance shift in $S_{11}$ of up to 0.72 GHz as ethanol concentration in aqueous solutions varied. On the other hand, the measurements revealed a 0.9-GHz shift in the $S_{11}$ resonance frequency as the ethanol concentration increased from 0% to 90%. The simulated and measured reflection coefficients in each sample case are demonstrated in Fig. 9. The minor disparity in these results is due to the simulation tool’s inability to match physical parameters such as sample volume and temperature during measurements. Additionally, measurements on the fabricated sensor demonstrate a resonance shift of up to 0.128 GHz per 10% change in ethanol concentration.
The measured sensitivity in this study is compared to the previously proposed state-of-the-art resonator-based liquid sensors in Table III. It should be noted that the solute used in the measurements may also affect the resonance due to the difference in permittivity between it and the solvent. For example, some studies employed liquid samples other than alcohols, but their sensitivity is low, except for a study conducted by Bakir et al. in which kerosene was used as the solute. The chiral metamaterial structure based on three unit cells demonstrated a resonant shift of 280 MHz for measurements of IPA–water solutions with varying IPA from 10% to 90%. Higher sensitivity was obtained because of the strong chiral electromagnetic fields present in the chiral structure.

However, the sensing method in Ref. 12 utilizes waveguide structure and sample holder, which is challenging to incorporate in real-life portable applications.

In comparison, due to the lower frequency of operation, investigations employing alcohol samples demonstrated a relatively low sensitivity. For example, a complementary split-ring resonator sensor operating at 3.3 GHz included a capillary tube to retain the sample, which showed a sensitivity of 50 MHz per 10% change in ethanol concentration. However, the Q-factor increased in one study as the water proportion increased, which is consistent with our findings. In our work, we used ethanol as the solute, and the sensor demonstrated the most significant shift in resonance for varied ethanol concentrations compared to previously examined structures. Following the sensitivity comparison, it is worth emphasizing that using 5G-mm-wave frequencies increases the perturbation of S-parameters in response to liquid permittivity variations.

### Table III State-of-art liquid resonator-based liquid sensors.

| References | Solute  | Operating frequency (GHz) | Sensitivity (Δf/10%) (GHz) |
|------------|---------|---------------------------|----------------------------|
| 27         | Ethanol | 0.225                     | 0.0042                     |
| 16         | Ethanol | 2.3                       | 0.05                       |
| 17         | Methanol| 6.5                       | 0.015                      |
| 32         | Saline  | 11.6                      | 0.026                      |
| 34         | Isopropanol | 5.4                   | 0.03                       |
| 35         | Ethanol | 2.15                      | 0.034                      |
| 14         | Methanol| 2.7                       | 0.062                      |
| 33         | Magnesium sulphate | 2          | 0.0784                     |
| 36         | Ethanol | 5.5                       | 0.085                      |
| 37         | Ethanol | 4                         | 0.095                      |
| 12         | Kerosene| 9.8                       | 0.16                       |
| This work  | Ethanol | 27.57                     | 0.178                      |

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### Conclusion

A novel microwave sensing technique featuring a replaceable resonator-based sensing layer for repeatable measurement without disconnecting the sensor from VNA has been discussed. The resonator sensor comprises two substrate layers: a substrate with the ground on the rear side for the transmission line connected with VNA and a sensing substrate layer with a resonator structure. The design was modeled and simulated in the 20–35 GHz frequency range. The sensor was constructed and tested to determine its performance in detecting the presence of ethanol in a liquid. A change in ethanol concentration in aqueous solutions changes the input impedance of the resonator’s transmission line, consequently influencing the reflection coefficient. Thus, the change in ethanol concentrations attains S11 perturbation. Experiments with water–alcohol solutions were conducted to analyze the sensor’s performance. Due to the sensor’s transition to a higher frequency, it demonstrated a higher sensitivity, up to 178 MHz per 10% increase of ethanol concentration in liquid volume, than the sensors operating at lower frequencies. Due to the lack of control over the sample volume, a small discrepancy between the simulated and measured results was observed. The results indicate that the sensor operating in the 5G-mm-wave band is susceptible to lossy liquids, as demonstrated by the concentrations of water and alcohol. At high frequencies, the electrical size of the sensor is substantially reduced, allowing for further miniaturization and possible integration into modern cell phones.

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Conflict of interest The authors declare that they have no conflict of interest.

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