Microwave sensor for liquid mixture identification based on composite right left hand-zero-order resonator for sensitivity improvement

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Microwave sensor for liquid mixture identification based on composite right left hand-zero-order resonator for sensitivity improvement

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Abstract

This work aims to present an improved version of the liquid mixture identification sensor, the proposed sensor is tested experimentally on mixture of water ethanol, the identification of liquid is based on the measurement of frequency displacement, and comparison with reference values of water ethanol. This device is based on metamaterial structure which is a composite right left hand (CRLH) resonator with zero-order resonator (ZOR). The CRLH in addition to its property of miniaturization effect, when combined with ZOR, the resonant frequency of various volume fraction are extended, which make the sensitivity higher. The high sensitivity of the sensor is obtained by an optimum choice of the CRLH components. The geometrical size of the sensor is 20 mm by 11 mm. It was printed on a RT/Duroid 5880 substrate with a very short testing surface area of 4 mm by 8 mm, the liquid is placed on the top side of the sensor, exactly on the CRLH structure. Three prototypes of sensors operating from 1 to 3 GHz are proposed, designed and simulated using the commercial software high-frequency structural simulator (HFSS). The main advantages of this work is first miaturization effect, second high sensitivity and finally a wide range of liquid can be tested with this sensor. To prove the working principle, ethanol with different volume fractions was adopted as a liquid under test, the obtained results present very good agreement with the literature and suggested that it is a miniaturized and high sensitive candidate (better than 1.38%) for liquid mixture identification.

KEYWORDS

CRLH, ethanol, liquid mixture, sensitivity, sensor, volume fraction, ZOR

1 | INTRODUCTION

Recently, the design of microwave sensors for liquid mixture identification[1–5] and dielectric characterization[6–10] is being the interest of many researchers due to their highly sensitive characteristics and ease to adopt in an industrial process, medical compositions, fuel and pharmaceuticals. Ethanol is a fuel source, a chemical solvent, an active ingredient in alcoholic drinks, as well as an antiseptic and disinfectant in medical applications. The quality of ethanol is often degraded by various contaminants such as water. Hence, the measurement of impurities in Ethanol has increasingly gained its popularity to meet the unabated demand in the industry. Several types of sensors such as optical and micro-electromechanical systems (MEMS) and microwave types have been proposed to accurately monitor the ethanol concentration.[1–10]

Metamaterial structures known as artificial materials have been integrated into microwave devices for the sake of high performances, such as wideband, high gain and miniaturization effect.[10,11] This is due to the unique property of metamaterial, which has the ability to produce dielectrics with negative permittivity, negative permeability, or both negative.[12,13] Researchers have used these materials to design devices with high performances that can be used in mobile communication, medical structures and all wireless devices.[14,16] The first research work done as an application of metamaterial on liquid identification was done using split-ring resonator (SRR).[17,18] Then complementary split-ring resonator (CSRR) was presented by Saadat et al.[19] and open complementary split-ring resonator (OCSSR) was proposed by Paris et al.[5] The most recent work was carried out by Chuma et al.[15] in which planar circular CSRR was studied. Similar work on complementary splitted ring resonator was done by Juan Domingo et al.,[20] another work based rectangular complementary ring resonator implemented on microstrip done by Wu et al.[21] Metamaterial also applied on horn antenna, Lashab et al.[22] have inserted CLL (capacitor loaded loop) inside the walls of rectangular horn antenna.

The composite right left-handed (CRLH) resonators are considered as metamaterial structures.[23,24] They have been used in wireless devices to improve electromagnetic structure performances, and these are the combination of the right hand (RH) and left hand (LH) electric equivalent circuits.[25,26] The resonant frequency of structure based on CRLH is characterized by the independence of its dimension.[27,28] The CRLH is based on the principle of transmission line (TL), they can be set up to obtain zero-order resonators (ZOR),[29,30] which is the first frequency or the dominant frequency of the circuit. The CRLH has also the advantage of frequency dilation on a short band width, and this criterion is used to increase the sensitivity of the sensor, miniaturization effect is common for all the structures based CRLH. This type of resonator is based on features considered as metamaterial behavior, first introduced by Sanada et al.,[31] later improved by Jang et al.[32] In the literature, tremendous research works have been proposed on liquid identification or dielectric characterization, probably the first one was presented by Bao et al.,[38] based on measurements he succeeded to identify dielectric of a liquid mixture such as methanol–ethanol.

The measurements were done by using an open-ended coaxial-probe method and analyzed with Debye function over a wide frequency range. Recently more interesting research work was carried out by Kashif Saeed[39] on dielectric characterization and others, such as Chretiennot et al.,[40] Benkhaoua et al.[2] Ebrahimi et al.[12,13,41] and Gennarelli et al.,[42] as well as Romeo et al.,[43] his work was based on capacitive sensing, all these works are dealing with liquid mixture with different designs, looking out for better or higher sensitivity. Some research works done on sensors dealing with the chemical solution were carried out by Salim et al.[44] In addition, more recent research works were performed on studying the complex permittivity or compact permittivity of the liquids,[45,46] while other research works were focusing on biological and glucose characterization.[47–50] By examining the previously published works,[1–5,16–19,23–47] it was found that the sensitivity and sensor size are still the fundamental constraints to limit microwave sensors being widely adopted. Hence, in this article, a miniaturized and improved sensitive microwave sensor with two ports is proposed to address this issue.

This sensor is loaded with CRLH-ZOR resonator on the top plane and ground plane. Three types of circuits were presented, designed and simulated. To verify the simulated results, a sensor prototype was built and measured based on the best-performed simulated model. To prove the concept, the prototype was tested under several fractions of the volume of water-ethanol liquids.

2 | SENSOR DESIGN CONCEPT AND THEORETICAL STUDY

2.1 | Theoretical Concept

The proposed sensor contains a compensated right left hand-based transmission line (CRLH-TL) unit cell on the upper side and a full ground plane on the bottom side. The transmission line (TL) structure is essential to realize a resonance without dependence on its physical dimension. This structure supports an infinite wavelength at its fundamental mode which is required to the ZOR. The

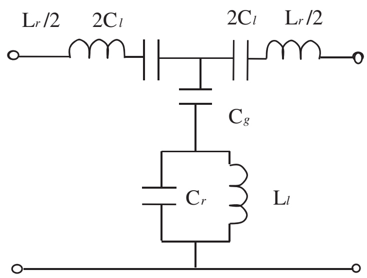


FIGURE 1 Equivalent circuit of the proposed sensor. (A) Top view, (B) bottom view

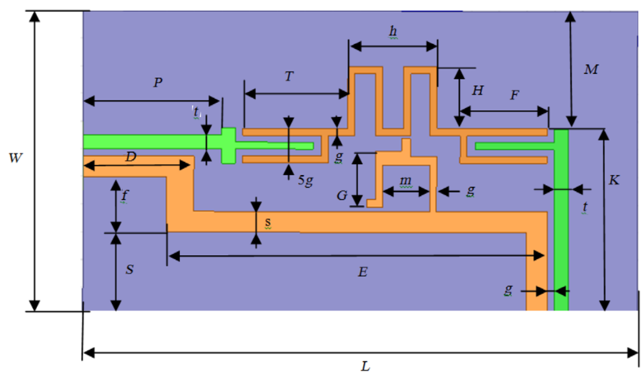


FIGURE 2 Proposed sensor 1

TABLE 1 Parameters of the proposed sensor in mm

L	*W*	*H*	*E*	*M*	*T*
20	11	2.25	13.75	4.25	3.8
h	*s*	*t*	*m*	*f*	*g*
3.2	0.75	0.5	1.7	2	0.25
K	*P*	*G*	*F*	*S*	*D*
6.75	5	2	3.2	3	4

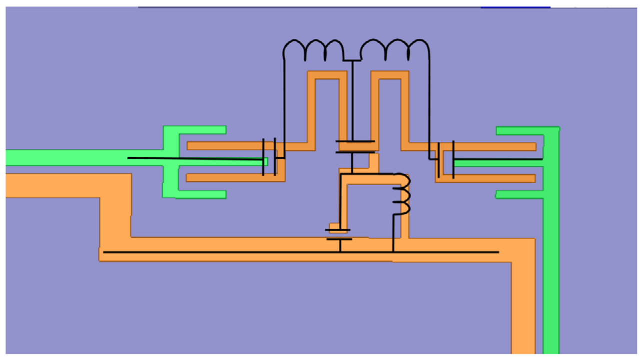


FIGURE 3 Proposed sensor 2

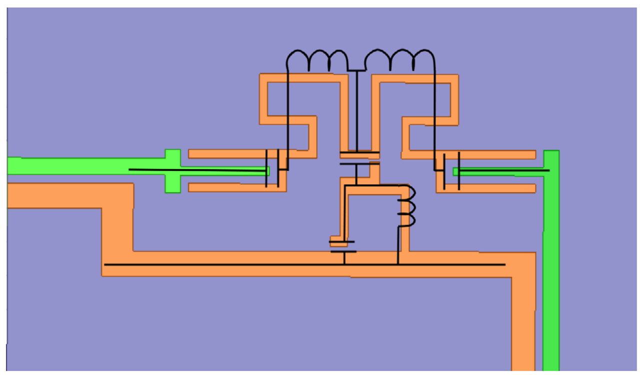


FIGURE 4 Proposed sensor 3

equivalent electric circuit of the proposed sensor is given below in Figure 1. The sensor is simulated then optimized using the full-wave simulator Ansys HFSS.

The resonant frequencies of the proposed CRLH unit cell can be derived from the dispersion relation in Equation (1). The ZOR, where $\beta l = 0$, occurs at ω_C. At the ZOR, the phase constant β becomes zero and infinite wavelength propagation is allowed. The negative first-order resonance, where $\beta l = -\pi$, also occurs at ω_z. The negative resonance supports backward wave propagation with the same field distribution of positive-order resonances. In addition, the positive-order resonances arise where $\beta l = +n\pi$, but the equations for those resonances are not given here for the sake of simplicity.

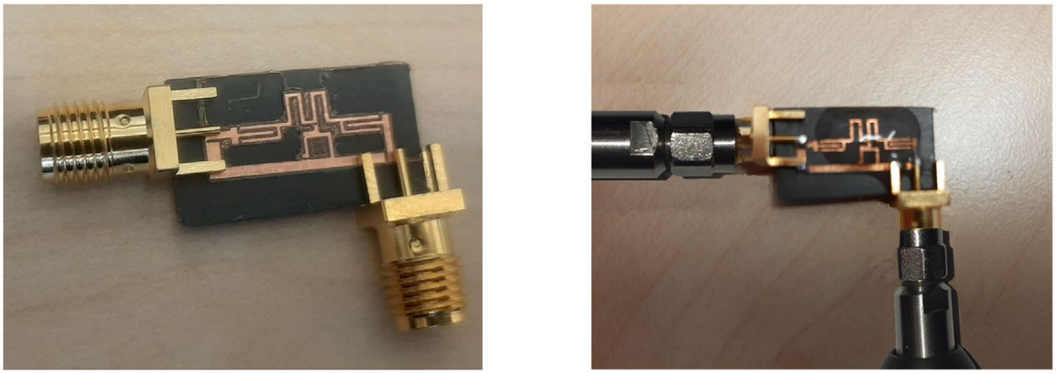
$$\beta l = cos^{-1}\left[1 + \frac{\left(\frac{\omega^2}{\omega_C^2} - 1\right)\left(\frac{\omega^2}{\omega_R^2} - \frac{C_G}{C_L}\right)}{2\left(1 - \frac{\omega^2}{\omega_z^2}\right)}\right] \tag{1}$$

where, $\omega_R = 1/\sqrt{L_R C_L}$, $\omega_C = 1/\sqrt{L_L C_R}$, $\omega_z = 1/\sqrt{L_L(C_G + C_R)}$.

One of the novel applications is the ZOR antenna, which is based on a CRLH-TL.[31] However, these CRLH-TL ZOR antennas typically suffer from narrow bandwidths. Thus, many attempts have been made to extend the bandwidth of MTM antennas.[28] In the work presented in reference 31, the ZOR characteristics were analyzed by using dispersion relation based on CRLH-TL theory and the full-wave simulation is carried out. In the CRLH unit cell, the impedance Z provides a serial resonance based on (L_R, C_L), whereas *Y* admittance provides a parallel resonance based on (L_L, C_R).[27] By implementing the same concept, the serial and parallel resonance values can be adjusted in order to optimize the best performance of the sensor.

2.2 | Geometrical dimension of the sensor

The first proposed sensor is presented in Figure. 2, the substrate is an Roger RT/Duroid 5880 laminate with



(A) (B)

FIGURE 5 Practical prototype of sensor 1 (A), with a drop of liquid mixture sample and Network Analyzer connectors (B)

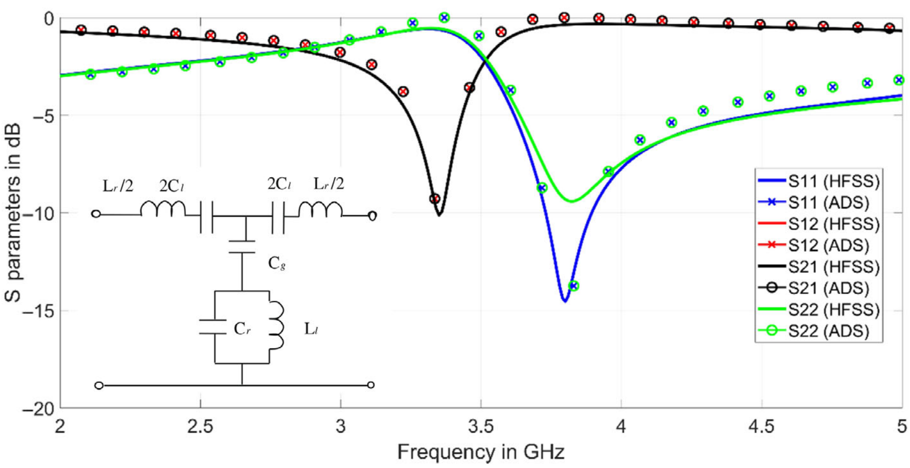


FIGURE 6 Simulated *S*-parameters of the microwave sensor (HFSS) and the equivalent circuit (ADS)

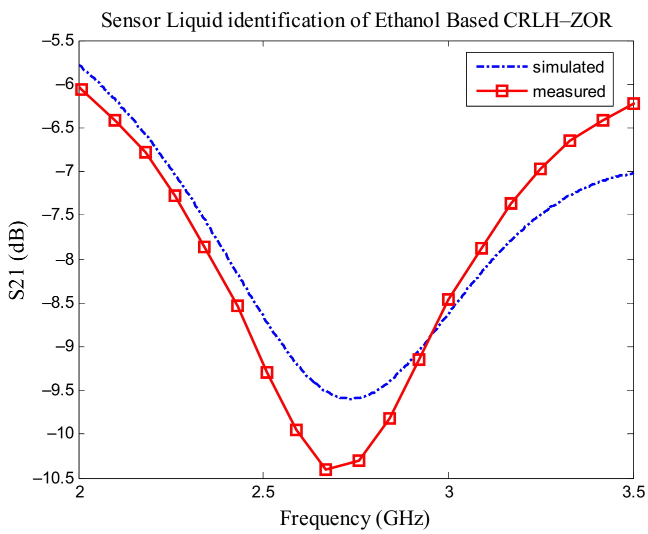


FIGURE 7 Simulated and measured transmission coefficient (S_{21}) of the sensor loaded with ethanol

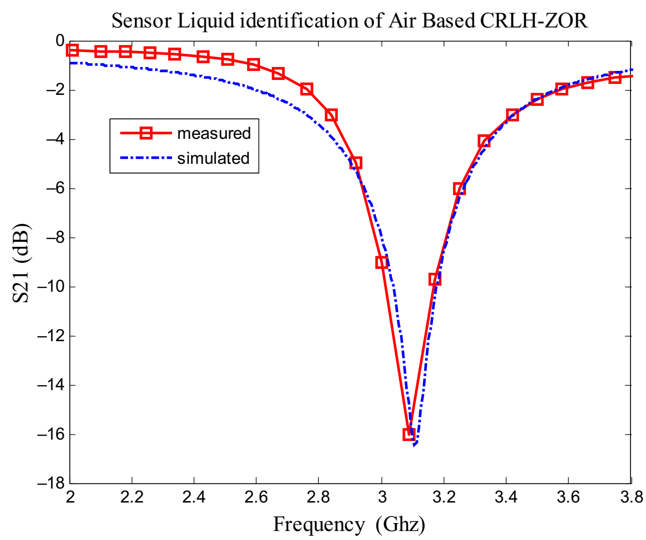


FIGURE 8 Simulated and measured transmission coefficient (S_{21}) of the sensor loaded with air

relative permittivity $\varepsilon_r = 2.2$ and dielectric loss tangent $\delta = 0.02$, the thickness of the substrate is 1.57 mm. The sensor is composed of CRLH–ZOR-based zeroth-order circuits with two ports. It consists of a coplanar structure on the top layer and a full ground plane at the bottom side.

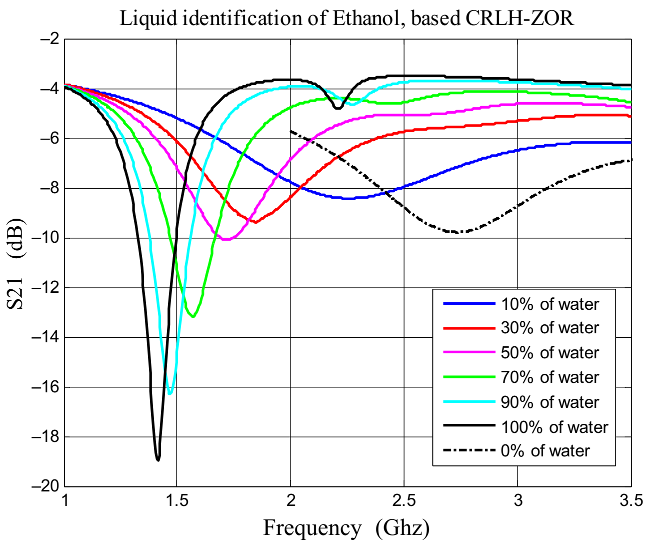


FIGURE 9 Transmission coefficient of the volume fraction of water–ethanol, sensor 1

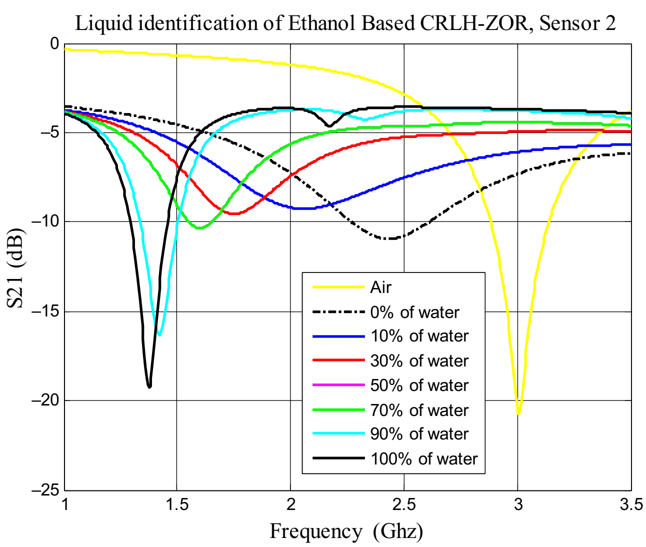


FIGURE 10 Transmission coefficient of the volume fraction of water–ethanol, sensor 2

The proximity coupling is used as the feed network to achieve a good impedance matching to 50 Ω, the geometrical dimension is given by Table 1.

The second proposed sensor is presented in Figure 3. In this sensor structure, the capacitances C_L are located at the two inputs of the ports, are designed with greater value as can be noticed in this figure.

The third proposed sensor is presented in Figure 4. In this type of structure, the inductors L_R are located at the input and output of the ports, are designed also with greater value as can be seen in this figure.

To validate the performance of the simulated model, a practical prototype of the first sensor is

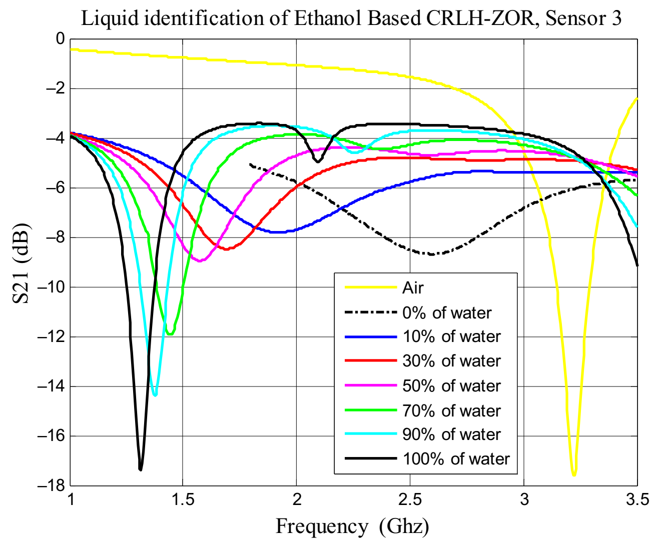


FIGURE 11 Transmission coefficient of the volume fraction of water–ethanol, sensor 3

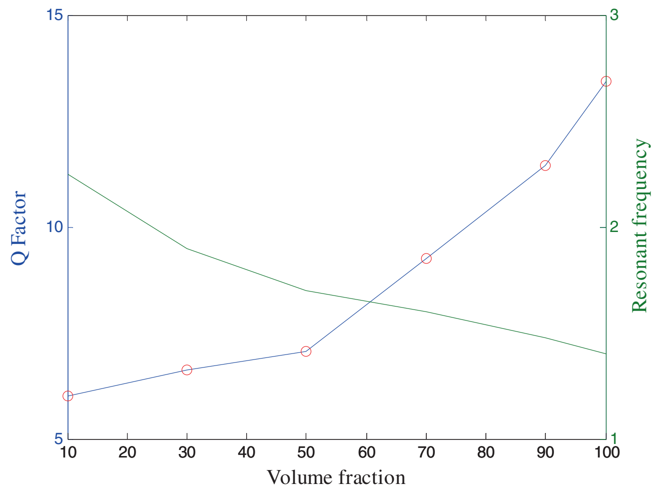


FIGURE 12 Q-factor and resonant frequency of the volume fraction of Ethanol, sensor 1

fabricated and tested with standard SMA connectors as shown in Figure 5.

3 | RESULTS AND DISCUSSION

To verify the proposed equivalent circuit for the microwave sensor as shown in Figures 1–4, Keysight ADS software were used to carry out this analysis. Interestingly, it was found that $L_R = 0.5$ pH, $C_L = 18.4$ pF, $C_G = 1.1$ pF, $L_L = 0.5$ nH, $C_R = 3.4$ pF (Figure 6).

A comparison between the simulated and measured transmission coefficients of the first sensor without liquid mixture (air) and with ethanol is given respectively in Figures 7 and 8. As can be noticed, a resonant frequency of the sensor loaded with air is found at 3.1 GHz, whereas the resonant frequency of the sensor loaded with ethanol is observed at 2.75 GHz, the figures show almost good agreement of the experimental results and the simulation.

To investigate the sensitivity of the proposed sensors, the transmission coefficients of the three sensors with volume fraction of water–ethanol were studied in Figures 9–11, respectively. This analysis was carried out with 0% of water and gradually increases to 100% water with 10% or 20% increment.

According to the results presented in Figures 8–10, all the sensors show a consistent performance which exhibits a shifting down of the resonant frequencies when each of the proposed sensors is gradually loaded from low-to-high volume fraction of water–ethanol.

The level of the sensitivity of the sensor can be determined by the frequency bandwidth of the ranges of the resonant frequencies when increasing the volume fraction of water–ethanol. From Figure 9, it is clear that the first sensor has a 1.35 GHz sensitivity bandwidth which starts from 1.4 to 2.75 GHz, while the second and third sensors possess bandwidth of 1.05 and 1.29 GHz which operates from 1.35 to 2.4 GHz, and 1.31 to 2.6 GHz, as depicted in Figures 10 and 11, respectively. Compared to the sensitivity of the performance of the sensor, sensor 1 performs better than sensors 2 and 3 where it demonstrates 0.3 and 0.06 GHz more bandwidth than sensors 2 and 3 respectively.

Figures 12 and 13 are deduced from Figure 9. They present the relation between the resonant frequency and the attenuation, as well as the relation between the resonant frequency and Q-factor for sensor 1. It is clear the relationship is almost linear, and the prediction of the dielectric value could be with fewer errors.

The dispersion diagram of the unit cell was calculated by the simulated on HFSS, Figure 14A, where the periodic boundary condition was applied on both sides of the unit cell and PML on the top side. According to the dispersion diagram Figure 14B, the ZOR, frequency is 1.6 GHz, for serial resonant frequency and shunt resonant frequency they meet at the fundamental frequency which is the ZOR frequency.

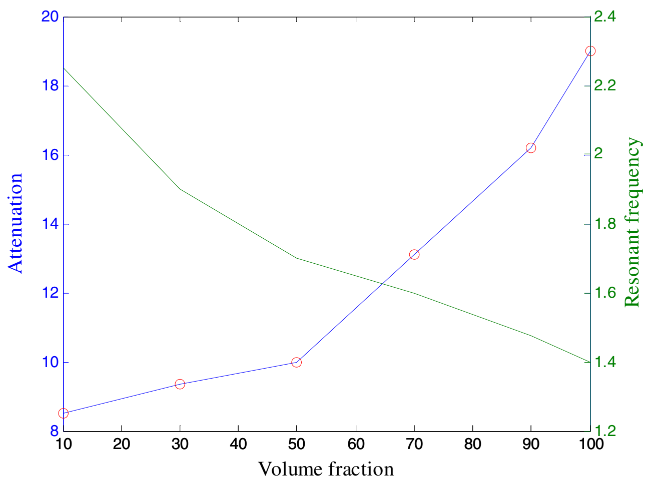


FIGURE 13 Attenuation and resonant frequency of the volume fraction of Ethanol, sensor 1

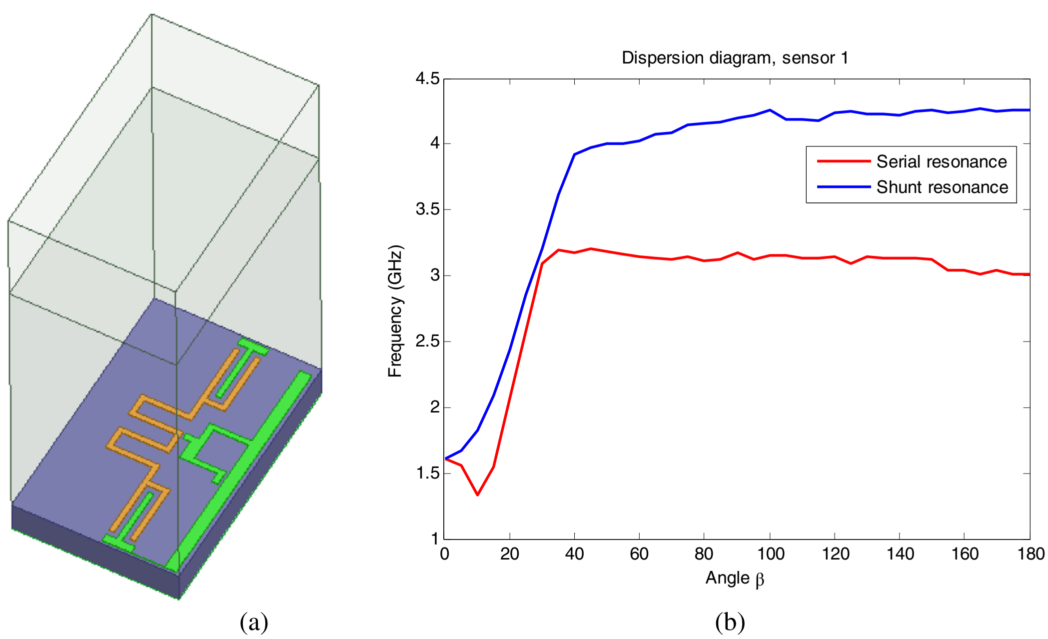


FIGURE 14 (A) Unit cell on HFSS and (B) dispersion diagram

The liquid under test is presented in Figure 15, the liquid is supposed to be placed on the top of the sensor in a rectangular shape, the input port and the output port are on the same side as shown in Figure 15, the testing surface dimension is 4 mm × 8 mm. According to the Debye relaxation model, the real part of the mixture permittivity can be expressed by using Equation (2) as given in reference 4, and based on the permittivity value given in Table 2.

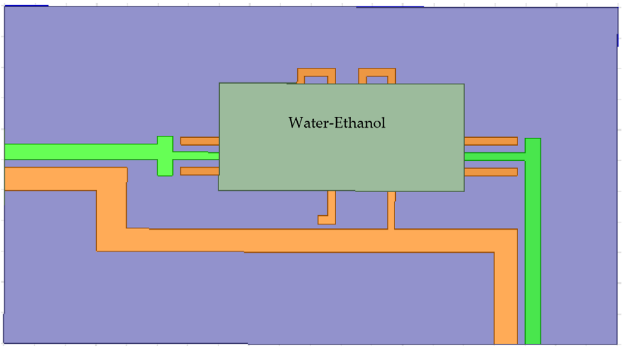


FIGURE 15 Position of the testing surface

TABLE 2 References values of complex permittivity to binary mixtures water–ethanol,[4] at about 2 GHz

	Ethanol	ϵ′	ϵ″
100%	0%	79.0	9.2
90%	10%	73.0	11.3
70%	30%	58.5	17.1
50%	50%	43%	17.1
30%	70%	29.0	16.0
10%	90%	15.5	12
0%	100%	9.5	8.1

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+\omega^2\tau^2} \tag{2}$$

where ε_s is the low-frequency permittivity, ε_∞ is the high-frequency permittivity, τ is the relaxation time, and ω is the radiated frequency. Due to the stability of the value of the permittivity around 2 GHz, the dispersion is not taken into account. The sensor sensitivity can be expressed by applying Equation (3) as in reference 4.

$$S = \frac{f_1 - f_0}{f_o d\varepsilon_r} \tag{3}$$

where f_o is the lower frequency of sensor (1.4 GHz) and f_1 is an upper frequency of sensor (2.75), and $d\varepsilon_r$ is the variation in the relative permittivity from volume fraction of 0% to 100% which is considered of (79–9.5 = 69.5). The simulated sensitivity has a maximum value given by Equation (4).

$$S1 = (2.75 - 1.4)/(1.4 \times 69.5) = 1.38\% \tag{4}$$

A sensitivity of 1.38%, which is a very high compared to the literature in references 39, 12, 2, 40, 43, 43, given respectively as 0.11%, 0.27%, 0.54%, 0.26%, 0.6% and 0.14%, this is well illustrated by Table 3.

4 | CONCLUSIONS

In this article, a very compact sensor based on CRLH resonator based on ZOR is designed for liquid mixture identification. Three types of sensors were proposed, designed and simulated with the commercial software HFSS in order to examine the effect of the capacitance and the inductance of the sensor. The experimental measurement was done on the first sensor load with air then loaded

TABLE 3 Comparison between different microwave sensors in literature

Microwave sensor structure	Frequency range (GHz)	Electrical dimension mm^2	Sensitivity %	Design complexity	References
Coplanar resonator	7–8	520	0.11	Moderate	39
CSRR	1.4–2.8	660	0.27	Easy	12
DSS-SRR	2.25–2.40	560	0.54	Moderate	2
Waveguide SRR	16–21	2.25	0.26	Complex	40
	0.9–1.1	990	0.6	Easy	43
Rectangular cavity	1.88–1.98	1.8	0.14	Complex	42
Circular CSRR	1.8–2.3	540	–	Easy	15
Rectangular CSRR	2.2–2.4	560	–	Easy	1
This work	1.4–3.1	220	1.38	Accurate	

with ethanol as the volume fraction of water–ethanol, the comparison between the experimental results and simulations was almost in good agreement, since the design was very small and the thickness of transmission line was very thin, small discrepancy appeared.

The obtained results have shown that the sensitivity of the sensor is very high, 1.38% was reached for the first proposed sensor compared to the literature and the dimension of the sensor is very compact, 220 mm^2, the operating frequency is lower compared to existing similar sensors 1.4 to 3.1 GHz, as well the testing surface of the sensor. The ZOR enables to extend the bandwidth of the sensor hence increasing the sensitivity of the sensor. The results suggested that by suitable choice of the capacitors and the inductors, the sensor can be optimized to deliver very high sensitivity in detecting the impurities of the ethanol concentration.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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