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Liquid Characterization of 2 GHz Complimentary Split Ring Resonator (CSRR) for Water Quality Applications

Muhammad Faris Sapuri [1], Mohd Khairil Adzhar Mahmood [2], Nur Emileen Abd Rashid [2], Nor Ayu Zakaria [1], Siti Amalina Enche Ab Rahim [2], Zuhani Ismail Khan [2]

[1] School of Electrical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
[2] Microwave Research Institute, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

***Abstract* – This study describes a complementary split-ring resonator (CSRR)-based planar microwave sensor. Its capability in detecting several samples which are based on the usual water contaminant in Malaysia was investigated. The CSRR sensor was designed with an unloaded resonant frequency of 2.0 GHz, and it was fabricated on an FR-4 substrate with a thickness of 1.6 mm and a dielectric constant of 4.3. The S-parameter responses of the sensor were measured under two conditions; i) unloaded and ii) loaded. For the latter, samples of tap water, salt water, isopropyl alcohol, filtered water and cooking oil were used to load the resonant element of the CSRR. The measurement result of unloaded CSRR shows that the designed sensor resonates at 1.99 GHz, which is in line with the simulation. The measurement results also showed that the presence of all samples caused the resonant frequency of the CSRR to shift, with filtered water and cooking oil showing the biggest frequency shifts (0.84 GHz and 0.96 GHz, respectively). A sensitivity analysis of the CSRR was carried out and it shows that it achieves 0.25% sensitivity. The proposed sensor may be a useful substitute for pricey commercial sensors for applications involving water quality because of the inexpensive materials and ease of fabrication.**

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Corresponding author: S. A. Enche Ab Rahim,
Microwave Research Institute, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
Email: amalinaabr@uitm.edu.my

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1. Introduction

Water pollution is one of the problems almost every developing country faces nowadays. In order to enlarge the economy and infrastructures, preserving the environment has always become the least priority. Human activities such as illegal logging, farming, agriculture, manufacturing industries and other activities can give an impact on the environment, especially on the natural water supply. In Malaysia, there are already cases of pollution of water sources such as rivers which affected the surroundings. On 21 December 2019, there were water shortages for about 5 days that occurred in Selangor, Malaysia. This is due to Selangor’s raw water supply, which is Sungai Semenyih, being polluted due to chemical dumping on it which affected 328,957 water user accounts [1]. In March 2019, river contamination happened at Pasir Gudang, Johor which is due to the dumping of toxic waste into the river. It affected more than 2,000 people and 111 nearby schools were ordered to be closed [2].

Water pollution is a trivial issue as it can affect all living things and the economy of the country. Health issues are one of the impacts that can be affected by water pollution. Afroz *et. al.* has reported that the consumption of contaminated water can cause a number of illnesses, including cholera, diarrhoea, and typhoid fever [3]. Furthermore, contaminated water sources can lead to a water outage. The water outage can affect all human activities, especially the industries that depend heavily on water to continue their operation. According to statistics done by the United Nations, 785 million people worldwide lack access to basic drinking water services. The research also stated that 1 out of 4 health care facilities such as hospital lacks clean water [4], [5]. This shows how serious water pollution can affect daily life.

Water pollution is mainly caused by human activities such as illegal dumping [2], farm fertilizer and livestock farming, [3], [6], [7], and industrial wastage [7], [8], [9] where the content of the wastewater contaminated natural water sources. The content in wastewater is bad for all living things that depend on natural water sources. To avoid consuming contaminated water, a monitoring system and a good sensor are needed to monitor and give a warning about the condition of water sources.

There are many commercial sensors available to be used in the environmental monitoring system. Depending on the objects or specimens to be monitored, the researcher can integrate the sensors with the microcontroller and other components to build a complete monitoring system. Eight conventional sensors were used on the water quality monitoring system which measures eight different content parameters in the water [10]. All these sensors are connected to the computer and the results obtained are available online. The popularity of conventional sensors to be used in monitoring applications is due to the sensors having good accuracy and being easily available on the market compared to the equipment used in industries or laboratories. However, due to the demand for high accuracy, the sensors can be too sensitive, and frequent calibration is needed. Some sensors with high accuracy tend to come with a high price [11], [12].

Besides the conventional sensors, there is another option that can be used as a sensor in monitoring systems. The planar microwave resonator, also referred to as a planar microwave sensor, is a sensor made of a resonant element and a transmission line. Microwave sensors have been favoured by the factory industries due to the advantages of the sensors which is they can do measurement non-destructively [13]. The microwave sensor manages to do a measurement without contact with the sample because it uses the penetrating waves of the sample. By using the penetrating waves, the anomalies in the sample can be detected without causing health issues to the worker there. The sensor has no fixed structures design which made it able to do a measurement on any sample. There are a few examples of microwave sensor design that has been proposed in past research such as ring resonator which can be used for water content detection [14] and gas sensor [15]. There were a variety of microwave sensor designs available, like the split-ring resonator (SRR), which is able to be used as a health monitoring application [16], liquid sensor [17], [18], [19] and displacement sensor [20] or the complementary split-ring resonator design which is also used as a water quality monitoring system [21], [22], [23].

Another design that can be used as a microwave sensor is a Complementary Split Ring Resonator (CSRR). Several research papers have discussed the use of the proposed design for liquid sensing applications. An application as a microwave sensor for water quality has been proposed by Zhang *et. al.*, where an array of CSRRs is used, where the author placed an array of CSRRs on a single board, with each CSRR having a different resonant frequency ranging from 1.36 GHz to 8.91 GHz [21]. As the paper discusses water quality measurement, the author has used the sample based on the real content of contaminated water. The sample included Nitrate (NO3), Phosphate (PO4), Ammonium (NH4), Lead (Pb), Mercury (Hg), Chromium+6 (CR+16), NaCl, pH, and Dissolved Oxygen (DO). The microwave sensor used in this has a plexiglass container around it, which is used to contain the liquid sample for testing purposes. The findings demonstrate that the suggested microwave sensor is capable of measuring a small number of samples in the water with a concentration as low as 10 µg/ml. The outcome demonstrates that the suggested microwave sensor has good sensitivity for usage as a water quality sensor. However, some regulations only approved the water as clean water or in Class I when the amount of foreign content is low as 0.1mg/l [24]. The microwave sensor design in this work has a good potential to be used as a water quality sensor, and with the improvements in the sensitivity, it should be able to measure the content as small as required by the authorities.

Another example of CSRR applications can be found in [23], where the author used the design of CSRR for microfluidic dielectric characterization. In this research, the author used a mixture of water-ethanol as a sample, which has various concentrations of water in ethanol. The mixture of water-ethanol will have a different concentration of water which is from 0% to 100%. The sample in this research is measured by allowing it to flow through the tube, where the tube is put on top of the CSRR. The result from this research shows that there is a different shift of frequency for every different concentration of mixture used. The change in frequency indicates that the microwave sensor can measure mixtures of water-ethanol at various concentrations. By using these properties of microwave sensors, it is not limited to using this microwave sensor for a mixture of water-ethanol only. It is possible to measure the concentrations of other mixtures.

Microwave sensors typically rely on planar resonators to generate their electromagnetic waves. These waves can be influenced by the presence of nearby materials or elements, which can cause them to be absorbed.

This phenomenon has been described by Liu et al. [25], who showed that material with higher electrical conductivity tends to absorb more electromagnetic energy. Since different materials would have varying electrical conductivities, this idea can be used in the development of microwave sensors. However, contaminants can change the sample's electrical conductivity and dielectric properties when testing liquid samples, making it challenging to precisely characterize the sample. Nonetheless, by carefully accounting for the unique electrical properties of each sample, accurate measurements can still be obtained using microwave sensors based on planar resonators.

Table 1. Water classes according to the NWQS [24]

PARAMETER	**UNIT**	**CLASS**					
		I	**IIA**	**IIB**	**III**	**IV**	**V**
Ammoniacal Nitrogen (NH3-N)	mg/l	0.1	0.3	0.3	0.9	2.7	>2.7
Biochemical Oxygen Demand (BOD)	mg/l	1	3	3	6	12	>12
Chemical Oxygen Demand	mg/l	10	25	25	50	100	>100
Dissolved Oxygen (DO)	mg/l	7	5-7	5-7	3-5	<3	<1
pH	-	6.5-8.5	6-9	6-9	5-9	5-9	-
Colour	TCU	15	150	150	-	-	-
Electrical Conductivity	µS/cm	1000	1000	-	-	6000	-
Floatables	-	N	N	N	-	-	-
Odour	-	N	N	N	-	-	-
Salinity	Ppt	0.5	1	-	-	2	-
Taste	-	N	N	N	-	-	-
Total Dissolved Solid	mg/l	500	1000	-	-	4000	-
Total Suspended Solid	mg/l	25	50	50	150	300	300
Temperature	^{o}C	-	Normal + 2^{o}C	-	Normal + 2^{o}C	-	-
Turbidity	NTU	5	50	50	-	-	-
Faecal Coliform	count/100 ml	10	100	400	5000 $(20000)^{a}$	5000 $(20000)^{a}$	-
Total Coliform	count/100 ml	100	5000	5000	50000	50000	>50000

These example of past research shows that it is possible to use microwave sensor, especially CSRR as liquid microwave sensor. However, the sample used in the past research is very limited and there are not many samples based on real contaminated water such as Ammoniacal Nitrogen (NH3-N), which is one of the contents in contaminated water. The National Water Quality Standard for Malaysia (NWQS) specifies that NH3-N content exceeding 0.9mg/l is deemed unsafe and requires treatment. Table 1 shows the water classes according to the NWQS, provided by the Department of Environment Malaysia [24]. This standard shows by having a sensor to differentiate the types of content alone is not enough to indicate the conditions of the water. To measure the real contaminated water, the sensor should be able to measure the samples with different concentrations.

The planar Complementary Split Ring Resonator (CSRR) is described in this study as a water quality sensor for a variety of samples, such as cooking oil, isopropyl alcohol, salt water, tap water, and filtered water.

The simulation outcomes show that the CSRR's structure is capable of accurately differentiating between various liquid samples deposited upon it. These findings were corroborated by the measurements using fabricated CSRR, which show that the sensor has great potential for use in a variety of water quality applications. Moving forward, future research will focus on optimizing the sensor's design for specific applications, as well as exploring its potential for use in other fields, such as environmental monitoring.

2. The Major Content of Contaminated Water in Malaysia

Proper management of wastewater is crucial to prevent water pollution and protect public health. In Malaysia, the Environmental Quality Act 1974 requires all industries to treat their wastewater before discharging it [25]. Discharging untreated water can introduce hazardous contaminants, such as heavy metals and radioactive elements, into water sources [7]. The Department of Environment Malaysia has identified three major water pollutants in Malaysia's water sources, namely Biochemical Oxygen Demand (BOD), Suspended Solid (SS), and Ammoniacal Nitrogen (NH3-N) [3], [26].

BOD, which refers to the total dissolved oxygen needed by bacteria to break down dead aquatic organisms, is an important indicator of water quality. A high BOD level implies a drop in dissolved oxygen, which is necessary for aquatic species to survive [8]. Similarly, SS is a measure of solid waste that is unable to dissolve in water, while NH3-N is found in wastewater from sources such as livestock farms, fertilizers, and detergents [6], [27]. Failure to treat wastewater before discharge can result in the pollution of water sources with hazardous elements like heavy metals and radioactive substances. Industries in Malaysia are required to treat their wastewater before discharging it, in accordance with the Environmental Quality Act 1974, to regulate wastewater management.

2.1. Ammoniacal Nitrogen (NH3-N)

Ammonia is a substance that is in the form of colourless gases. While Ammoniacal Nitrogen (NH3-N) is a measurement of ionized Ammonia (NH3) or Ammonium (NH4+) content in the water [26]. In nature, Ammonia can be found in many living things such as animals and plants and also in rain [28]. However, there is also Ammonia that is formed due to human activities such as farming, factories and many more. Ammonia contamination can lead to many problems due to the fact that Ammonia is a toxic substance that can affect living things with a certain amount of it [6], [27]. The National Water Quality Standard Malaysia (NWQS) considers water with an NH3-N content of 0.1mg/l or lower as safe for use. However, if the NH3-N content is more than 0.3mg/l, treatment is required before it can be used [24]. It is important to understand the potential impact of ammonia on water quality, given the risks it poses to human health and the environment.

2.2. Oil

Palm oil is one of Malaysia's largest exports. As one of the largest producers and exporters of palm oil in the world, Malaysia's palm oil industry is a significant contributor to river pollution in the country. According to Afroz *et. al*., [3], palm oil mill is one of the sources of river pollution in Malaysia. Malaysia is also one of the countries that produce its petroleum. To avoid the water sources being contaminated with oil, Act 127 was used to prevent people from dumping the oil into the water sources [25]. NWQS has specifically categorized the oil contamination into two which are mineral oil (petroleum, diesel, etc) and emulsified or edible oil (palm oil, coconut oil, etc). According to NWQS, water contaminated with at least 40µg/l of mineral oil is needed to be treated. While for emulsified and edible oil, having water with 7000µg/l of oil is not safe and needed to be treated [24]. It is important to make a distinction between these two types of oil contamination, as they may have different impacts on water quality and require different treatment methods.

2.3. Salinity

The level of salt concentration in water, which is commonly known as salinity [29], can adversely affect freshwater ecosystems and their use for human purposes. Although freshwater sources typically have a low concentration of dissolved salt, human activities such as irrigation, mining, and agriculture can cause the salinization of freshwater. High levels of dissolved salt can change the properties of freshwater, including the pH, conductivity, and base cation of the water [30], which can impact aquatic life and disturb the ecosystem [31], [32], [33]. For example, some aquatic species are unable to adapt to saline water and can die as a result. The National Water Quality Standard Malaysia (NWQS) specifies that water with a salinity of 0.5 parts per thousand (ppt) is considered clean, while water with more than 2 ppt of dissolved salt requires treatment to make it safe for use [24].

3. Complementary Split Ring Resonator

The planar complementary split-ring resonator (CSRR) is another design for planar microwave resonators. The design consists of a substrate that is placed between a conductive plane and a ground plane. In this work, the design of CSRR is on the ground plane where it acts as the resonant element.

At the resonant frequency where the sensor's resonant element is produced, a transmission zero occurs. Typically, in the absence of other elements near the sensor, the transmitted power of the sensor will be entirely reflected at this resonant frequency. However, having any object or elements near or on the sensor will disrupt the resonant frequency. The change can be detected through either a shift in resonant frequency or a change in transmitted power. This change of frequency can be different for other elements based on the properties of the element itself.

3.1. Design of CSRR

As mentioned before, planar CSRR consists of three planes which are a transmission plane, substrate plane and ground plane. The ground plane is where the CSRR design is implemented; the copper layer of the ground plane will be removed in a shape known as a split ring, which resembles the letters "U" or "O" with one split gap on them.

The planar CSRR can also be modelled as an LC circuit as depicted in Figure 1 [34], [35], [36]. By having a specific value of inductance and capacitance, the resonant frequency can be expressed as in equation (1). The resonant frequency, which is determined by the specific values of inductance and capacitance, can be expressed using equation (1), which is based on Figure 1.

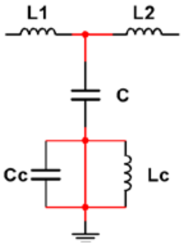
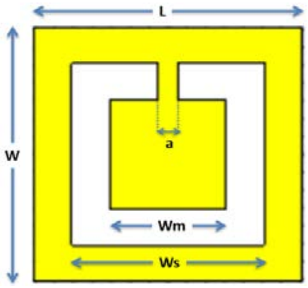


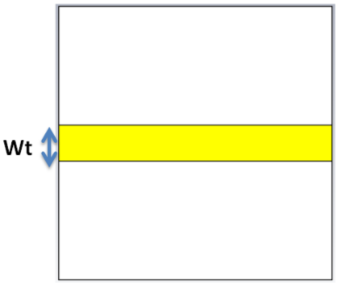
Figure 1. The equivalent circuit of CSRR

$$f_r = \frac{1}{2\pi\sqrt{L_c(C_c + C)}} \tag{1}$$

where L_1 and L_2 stand for the transmission line's total inductance, C for the coupling capacitance between it and the CSRR structure, and Cc and Lc for the CSRR structure's respective capacitance and inductance



(a)



(b)

Figure 2. The (a) structure of CSRR and (b) transmission line

Table 2. Parameters of planar CSRR sensor

Parameter	W (mm)
W	13
L	13
Ws	16
Wm	8
Wt	2.959
a	3

This study utilized CST simulation software to simulate the CSRR design, which was implemented on a 1.6 mm thick FR-4 substrate with a dielectric constant of 4.3. Figure 2 displays both the structure of CSRR and the transmission line of the sensor, while Table 2 presents the dimensions of the sensor designed for this study.

3.2. Properties of the Samples

In this study, three materials commonly found in irrigation water, including contaminated irrigation water in Malaysia, were selected as samples for the simulation process. Table 3 shows the properties of those samples including electrical conductivity and dielectric constant at room temperature.

Table 3. Properties of samples

Sample	Dielectric Constant	Electric Conductivity [S/m]
Air	1.00059	-
Distilled Water	78.4	5.55e-6
Oil	2.33	-
Ammonia	22	0.003

The properties used are based on the template prepared by the CST simulation software. However, in reality, a variety of elements, including changes in temperature and sample contaminants, may influence the dielectric properties of the samples.

4. Results and Discussion

As mentioned previously, the designed sensor was simulated by using CST simulation software. Once the performance of the design was verified, the sensor was fabricated and measured. This includes the measurement of unloaded CSRR and loaded CSRR, where various liquid samples were used as a sample under test. Each sample was loaded on the top of the CSRR structure for measurement. The performance of the measured sensor was then compared with the ones from the literature for validation.

4.1. Simulation of CSRR

In this work, the samples used were put on the surface of the CSRR. The samples used in the simulation were set to have a thickness of 1 mm, with the same width and length as the CSRR structure. The copper plane is 0.035 mm in height, while the substrate plane is 1.6 mm in height. Figure 3 depicts the sensor's cross-section with a sample.

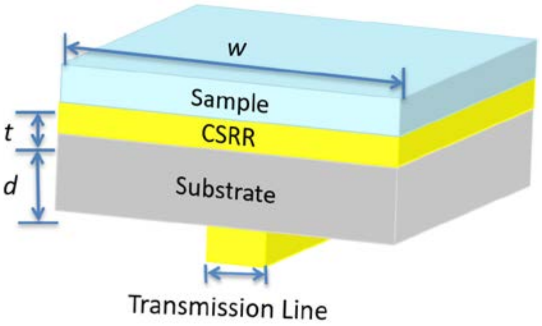


Figure 3. Cross-section of CSRR

The simulations of CSRR sensor started with the sensor without any sample on it which gives the simulated value of $\omega^2_{(\text{unloaded})}$ in Eq. (4). Next, the sensor was simulated by loading it with samples in order to obtain the value for $\omega^2_{(\text{loaded})}$. In this simulation, the value of the sample dielectric properties in Table was used. The developed sensor's simulated S_{21} response is shown in Figure 4. While the sensor resonates at 1.99 GHz when it is empty, it resonates at 1.32 GHz for ammonia, 2.178 GHz for distilled water, and 1.89 GHz for oil when it is loaded to the CSRR. It can be seen that the results of loaded CSRR are shifting away from the unloaded CSRR. The frequency shift of ammonia is furthest while oil is nearest with the frequency of unloaded CSRR. Table 4 shows the shift of frequency of loaded CSRR based on the simulation results.

Table 4. The Simulation CSRR Sensors' Frequency Shift

Type of samples	Frequency shift, Δf (GHz)
Distilled Water	0.67
Oil	0.10
Ammonia	0.19

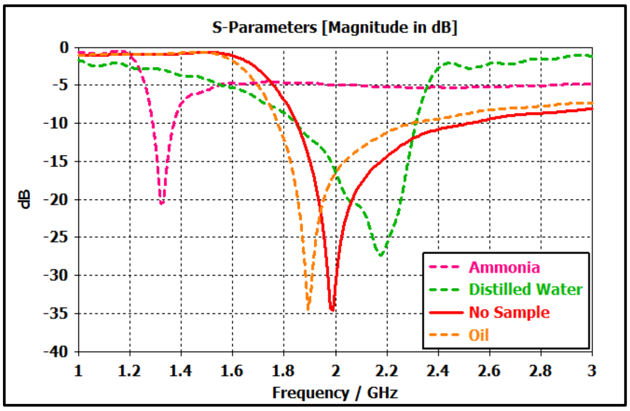


Figure 4. Simulated S_{21} of the unloaded (no sample) and loaded sensor.

4.2. Measurement of CSRR

The CSRR sensor was designed on an FR-4 substrate with a 1.6 mm thickness and a dielectric constant of 4.3. Figure 5 shows the measurement setup, which involves connecting a CSRR sensor to a Vector Network Analyzer (VNA). The unloaded sensor's S-parameter response was initially measured. Then, sequentially, the sensor was loaded with samples and the S-parameter response of the loaded sensor was measured.

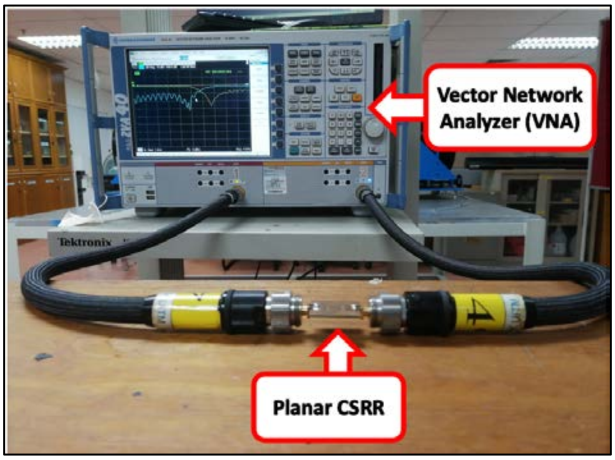


Figure 5. Measurement setup

The measurement shows that the sensor resonates at 1.99 GHz, which is much in line with the simulation shown in Figure 6.

However, the measured magnitude of S_{21} is much lower than the simulated result, which is -51.27 dB compared to -34.71 dB in the simulation. This indicates that the sensor exhibits a good stopband characteristic.

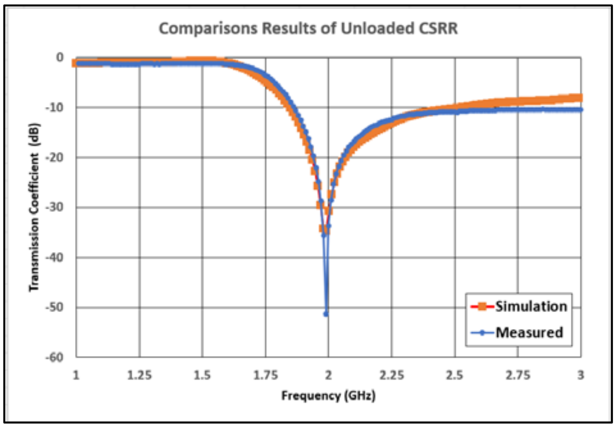


Figure 6. Comparison results between simulation and measurement of S_{21} for unloaded CSRR

To load the CSRR, these samples were used; tap water, filtered water, palm-based cooking oil, isopropyl alcohol (IPA), and saltwater. A few drops of the sample were put at the ring gap of the CSRR each time, and the S_{21} was measured.

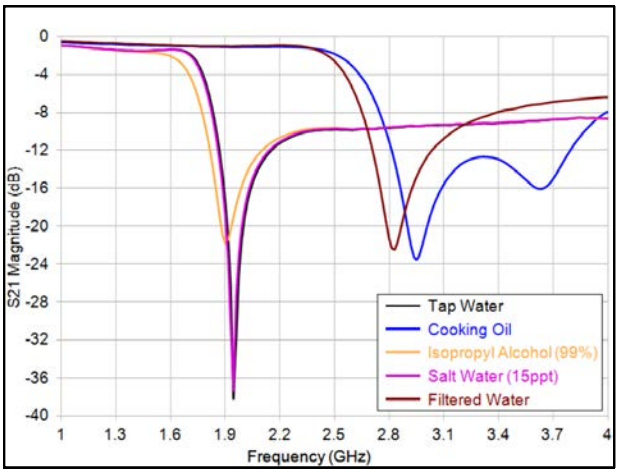


Figure 7. Measured S_{21} performance of loaded fabricated CSRR.

Based on the results shown in Figure 7, the CSRR reacts differently for every sample used. The cooking oil sample produced the largest frequency shift, with a shift of 0.96 GHz from the unloaded CSRR. On the other hand, the tap water and saltwater samples resulted in the shortest frequency shift of only 45MHz from the unloaded CSRR. Both tap water and salt water also have almost the same magnitude of S_{21} which is -38.28 dB and -37.41 dB while the magnitude for IPA is the highest compared to all samples which is -21.82 dB. The shift of frequency of loaded CSRR for all samples is summarized in Table 5.

Table 5. The change of Measured CSRR Sensors' Frequency

Type of samples	Frequency shift, Δf (GHz)
Tap Water	0.045
Filtered Water	0.840
Cooking Oil	0.960
Isopropyl Alcohol	0.090
Salt Water	0.045

The frequency changes occur due to the dielectric properties of the sample. Samples with higher conductivity absorb more electromagnetic (EM) energy, resulting in a greater frequency shift [38], [37]. Referring to Table 4, it is evident that the sample's electrical conductivity and dielectric constant have an impact on the frequency change for the loaded CSRR in simulated results. However, while comparing the simulated and measured results, there is a slight difference in the frequency shift. This is because the liquid samples used in this work are prone to the risk of contamination from the surroundings (e.g. dust or any unnoticeable particles), which can affect the purity of the sample itself. The sample's dielectric properties and electrical conductivity may be influenced by these contaminants. Another factor is the temperature of the surroundings, where for most of the liquid, its dielectric properties change when its temperature changes [38].

4.3. *Sensitivity of the CSRR*

The observed variations in frequency response for different samples in this study are attributed to the sensitivity of the microwave sensor. The ability of the microwave sensor to identify the changes in the sample's dielectric properties determines the sensor's sensitivity.

To determine the sensitivity of the microwave sensor used in this work, the resonant frequency of the unloaded CSRR was compared with the frequency response of the loaded CSRR. The sensitivity of the CSRR is defined by Equation (2) [39], [40], [41].

$$S = \frac{|f_o - f_{\varepsilon r}|}{f_o(\varepsilon_r - 1)} \, x \, 100 \tag{2}$$

where f_o is the resonant frequency of the microwave sensor designed in this work while $f_{\varepsilon r}$ represents the frequency response of the sample loaded on the microwave sensor. The microwave sensor's sample's dielectric constant is indicated by the symbol ε_r.

In this study, isopropyl alcohol was selected as the sample to evaluate the sensitivity of the microwave sensor.

Previous studies have reported that the dielectric constant of isopropyl alcohol can range between 18.62 to 19.41 [42], [43], [44]. In this work, the sensitivity of the proposed microwave sensor was obtained using the average dielectric constant of isopropyl alcohol from the literature. Table 7 shows a comparison of the sensitivity between the microwave sensor presented in this study and from the literatures. This table illustrates that the sensitivity of the proposed CSRR microwave sensor is higher compared to the sensor used in past research.

Table 7. The sensitivity comparisons of microwave sensors from the literature

References	Resonant Frequency (GHz)	Dielectric Constant, εr	Sensitivity, *S*
[45]	0.9	27.7-80.8	0.200
[40]	1.2	1-80.1	0.623
[46]	1.9	9-80	0.081
[23]	2	9-79.5	0.238
[47]	2.4	-	0.214
This Work	1.99	18.62-19.41	0.251

5. Conclusion

A planar Complementary Split Ring Resonator (CSRR) for applications in liquid sensing is presented in this research. As concerns about water quality and pollution's impact on aquatic ecosystems continue to rise, real-time monitoring systems that can identify numerous water quality indices are urgently needed. The CSRR designed in this work was fabricated on an FR-4 PCB and had a resonant frequency of 1.99 GHz when unloaded. CST simulation results demonstrated the ability of the CSRR to measure different types of samples loaded onto it. However, the fabricated CSRR was subject to the effects of its surroundings, such as temperature and impurities in the sample, which could cause slight variations in the measurement results. Nonetheless, changes in the frequency response and magnitude of the CSRR were able to differentiate between different types of samples. For instance, specific pollutants or contaminants have unique dielectric properties that affect the resonance frequency and amplitude of the CSRR, making it a promising tool for identifying and quantifying such contaminants in water quality monitoring applications.

To validate the performance of the fabricated CSRR, multiple liquid samples were tested, including tap water, salt water, IPA, filtered water, and cooking oil.

The frequency response of the sample was obtained by placing a small amount of the sample at the ring gap of the CSRR and connecting the CSRR to a Vector Network Analyzer (VNA) for measurement. The findings revealed that the CSRR had the capability to differentiate between various samples by analysing their frequency responses. The tap water and saltwater samples demonstrated a marginal frequency shift from the resonant frequency of the CSRR, which was 1.945 GHz, whereas the IPA sample displayed a slightly higher shift at 1.90 GHz. In contrast, the filtered water and cooking oil samples showed a much larger shift in frequency, at 2.83 GHz and 2.95 GHz, respectively. The results indicate that the CSRR can effectively distinguish between liquid samples based on their dielectric properties, which can be affected by various factors, including the presence of contaminants and the temperature of the sample. The comparison with the distilled water sample, which exhibited a resonance frequency close to the unloaded CSRR, provides insight into the unique characteristics of each liquid. These findings hold significant promise for the development of water quality sensors and related applications, such as the detection and quantification of contaminants in real-time monitoring systems.

To further enhance the accuracy and practicality of this microwave sensor, future work should focus on confirming the dielectric properties and electric conductivity of the samples tested. Confirming those properties will help us better understand how the properties of the sample and variations in frequency during the measurement process relate to one another. In addition, future work should involve testing the CSRR with real contaminated water samples that contain specific types of contaminants or pollutants. The CSRR has the potential to be a useful instrument for water quality monitoring in various kinds of applications, including environmental monitoring, industrial operations, and public health, if it can precisely measure the quality or content of these samples.

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