

CSRR based microstrip patch antenna sensor for the analysis of water and milk quality

Priyanka^a, Sonia bansal^a & Preet Kaur^{b*}

^aDepartment of Physics, J.C. Bose University of Science & Technology, YMCA, Faridabad 121 006, India

^bDepartment of Electronics Engineering, J.C. Bose University of Science & Technology, YMCA, Faridabad 121 006, India

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This research proposes a compact CSRR-based rectangular microstrip patch antenna sensor for sensing and identifying water and milk quality. The proposed sensor has been engineered to detect water quality and adulterate milk with water, caustic soda, sodium carbonate, ammonium sulphate, and urea with high accuracy and sensitivity. This novel work uses the same antenna sensor for water and milk adulteration and can also be used for wireless local area network (WLAN) applications. The proposed sensor is compact, simple to operate, affordable, highly sensitive, reliable, and can also be used to evaluate liquid quality. The design of the sensor has been built on a FR4 substrate with dimensions of 35 mm X 43 mm X 1.6 mm. The suggested sensor has been fabricated and validated experimentally to function at a frequency of 2.4 GHz, which matches the simulated results produced by HFSS extremely well. The antenna sensor has a good radiation pattern with 2.5 dBi gain and a quality factor (Q) of 60.25. The proposed antenna sensor is very valuable in liquid quality analysis and wireless communication.

Keywords: Adulteration, Antenna sensor, Complementary split ring resonator (CSRR), Milk, Water

1 Introduction

With the advancement of technology in the electronics and wireless industry, antenna sensors that have simplicity, passive operation, small size and versatility have attracted a lot of interest¹. Various antenna sensor-based approaches have recently been presented to identify quality of water and adulteration of milk²⁻⁵. Due to industrial expansion and rapid urbanization, drinking water has been contaminated⁶. By only looking through the sample of water, water quality may not be validated. Even when something seems clean and nice, it might still be polluted. Consuming unclean water puts one at risk for diarrhea, typhoid fever, cholera, and other illnesses. Water is essential for the fundamental life of both plants and animals. To put it simply, all living things require plenty of high-quality water to survive. Testing the water's purity is therefore necessary⁷⁻⁹. Total dissolved solids (TDS) is the term used to indicate the amount of micro-organic particles and inorganic salts that exist in the sample of water. The TDS level in the water sample may be determined using two traditional techniques¹⁰. The gravimetric analysis methodology is the first approach. This method determines TDS via evaporation of the liquid sample and figuring out the mass of the leftover particles. Although difficult, this approach is accurate¹¹.

The second technique involves using a regular conductivity meter. By inserting the meter inside the water sample, this approach determines the TDS level. The conductivity of the water sample affects the TDS value. Although this method is simpler to test, it has poor accuracy¹². Both of these techniques need technical knowledge and are generally laboratory-based. The quality and composition of foods are the most important critical factors at all stages in the food-producing industry. However, dishonest manufacturers now often adulterate food to boost profits¹³. Adulteration can happen accidentally or on purpose. Milk and products made from milk, water, juices, edible oils, and other liquids are frequently found to be contaminated in the marketplace. These fluids are in high demand, thus purposeful adulterants including urea, chalk powder, mineral oil, starch, and toxic colors are added to them¹⁴⁻¹⁶. The detection of food adulteration has been made possible by several standard techniques, including chemical and mid-infrared spectroscopy¹⁷.

These traditional techniques for analyzing water and food qualities need expensive and complex equipment. Such instrumental evaluation approaches are laborious, costly, time-consuming, and need meticulous sample preparation. Due to its non-invasive qualities, real-time, capacity for penetration sensing, and extremely precise detection techniques, microwave measuring is a great sensing tool¹⁸.

*Corresponding author (E-mail:preetmoar@gmail.com)

In this research, a user-friendly CSRR-based antenna sensor is designed to address the aforementioned drawbacks of conventional approaches. The proposed sensor has the unique feature of being able to evaluate the quality of water and milk internally without impairing the quality of either. This sensor is less complicated since it doesn't require any hazardous materials or expensive machinery. It performs well in terms of accuracy and sensitivity, to identify quality of water and adulteration in various milk samples. Further, this sensor performs faster and makes it simple to comprehend the data. The presented antenna sensor is a CSRR-based rectangular MPA which resonates at a frequency of 2.4 GHz with -28.35 dB return loss and a good matching impedance. It possesses a Q -factor of 60.25 and a good numerical sensitivity (NS) of 0.42. As a result, the suggested inexpensive antenna functions as a liquid sensor and shows to be a reliable instrument for identifying milk adulteration and water quality issues.

2 Materials and Methods

2.1 Design and fabrication of antenna sensor

The proposed antenna is designed on a low-cost FR4 substrate having dielectric constant = 4.4, loss tangent = 0.0025, and height = 1.6 mm. By using the transmission line equations (1-3), it is possible to compute the length and width of a patch antenna sensor operating at 2.4 GHz¹⁹.

$$W_p = \frac{c}{2 f_o \sqrt{\frac{\epsilon_r + 1}{2}}} \quad \dots(1)$$

$$\epsilon_{reff} = \frac{(\epsilon_r + 1)}{2} + \frac{(\epsilon_r - 1)}{2} \left(1 + \frac{12h}{W} \right)^{-1/2} \quad \dots(2)$$

$$L_p = \frac{c}{2 f_o \sqrt{\epsilon_{reff}}} \quad \dots(3)$$

Here, W_p represents the width of the rectangular patch, L_p denotes the length, ϵ_r presents the relative permittivity of the substrate, c gives the velocity of light, and ϵ_{reff} denotes the effective dielectric constant. HFSS software is used to model and optimize the antenna sensor geometry parameters once they have been calculated using the aforementioned equations. Table 1 gives the dimensions for the CSRR-based microstrip antenna sensor. The shape and configuration of the suggested antenna sensor is shown in Fig. 1, and the antenna sensor prototype that was actually built is shown in Fig. 2.

Table 1 — Dimensions for the CSRR-based patch antenna sensor

Parameter	Values(mm)
Substrate	L=35; W=43
Patch	$L_p=26.4; W_p=30$
Ground	L=35; W=43
Substrate Thickness	$h=1.6$
Side length of the outer ring	$L_1 = 8$ mm
Side length of the inner ring	$L_2 = 4$ mm
Width of the Split gap	$s = 1$ mm
Distance between rings and width of the rings	$g = 1$ mm

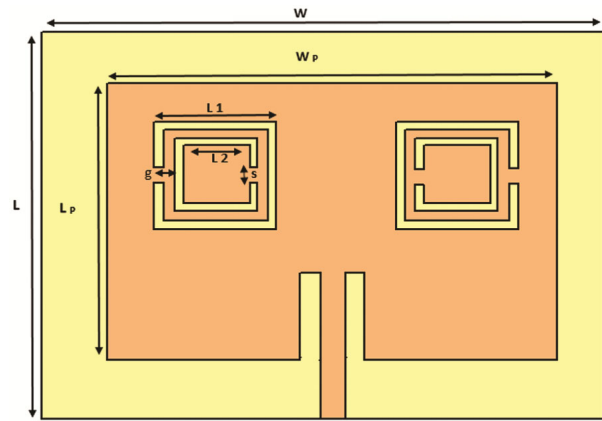


Fig. 1 — Model of the proposed antenna sensor in HFSS software.

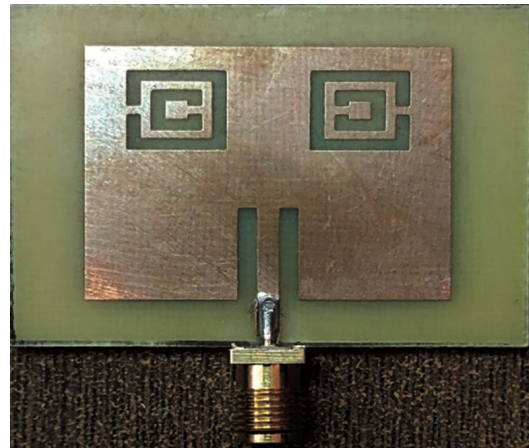


Fig. 2 — Fabricated antenna sensor.

2.2 Characterization of antenna sensor

The Anritsu MS2027C Handheld VNA (Vector network analyzer) Master was used for testing the fabricated antenna. It is capable of measuring frequencies between 700 MHz to 14 GHz. In Fig. 3(a) the simulated result indicates a reflection coefficient of -24.32 dB at a resonant frequency of 2.4 GHz and the measured result has a return loss of -28.35 dB at a resonant frequency of 2.41 GHz. The simulated return loss and the experimental one exhibit good

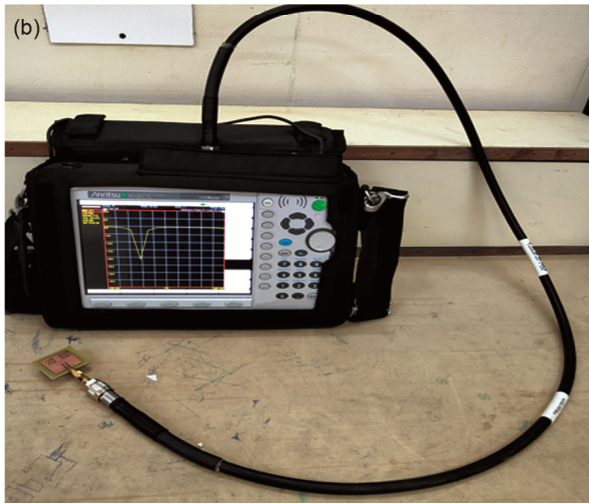
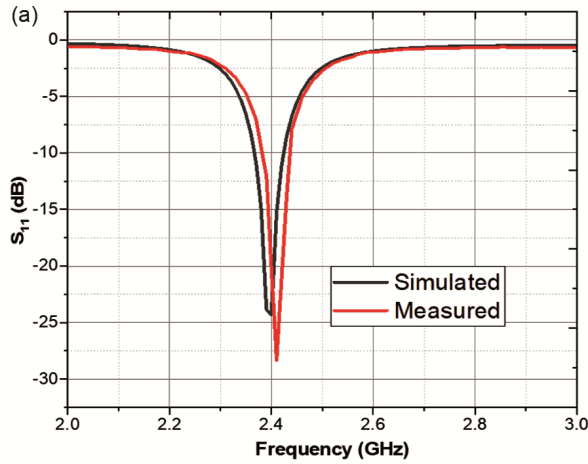


Fig. 3 — (a) Simulated and measured antenna reflection coefficient responses and (b) Analyzing reflection coefficient *via* a vector network analyzer.

agreement. Figure 3(b) shows the measurement setup for testing the fabricated antenna using VNA (MS207C). The measurement was done at the J.C. Bose University of Science and Technology, YMCA, Faridabad, India, Microwave Laboratory in the Electronics Engineering Department. The value of the quality factor (Q) is given by²⁰.

$$Q = \frac{f_0}{\Delta f} \quad \dots(4)$$

Where f_0 gives the resonant frequency and Δf stands for the bandwidth of the resonator. Using Eq. (4), the Q -factor for the proposed antenna sensor is 60.25. The numerical sensitivity⁴ of the antenna sensor is 0.42%. The gain of the antenna is 2.5 dBi. Figure 4 depicts the radiation pattern of the recommended antenna at 2.4 GHz in the E and H planes.

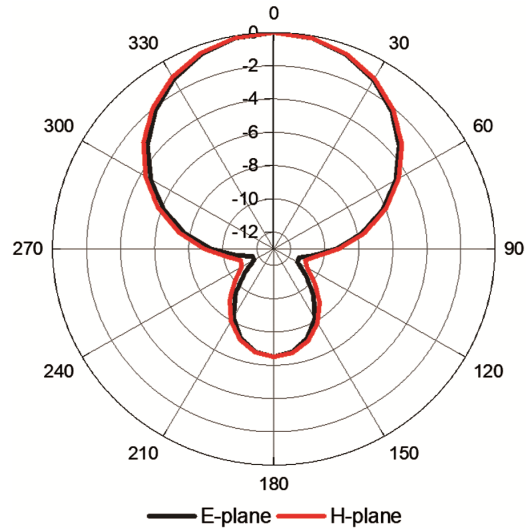


Fig. 4 — Radiation pattern at 2.4 GHz.

2.3 MPA as a liquid sensor

For a microwave sensing system, the basic interaction between the medium of propagation and microwaves is controlled by the medium's relative permittivity (ϵ_r) and permeability (μ_r):

$$\epsilon_r = \epsilon' - j\epsilon'' \quad \dots(5)$$

$$\mu_r = \mu' - j\mu'' \quad \dots(6)$$

Where ϵ' denotes the capability of storing electrical energy (real permittivity), ϵ'' = imaginary permittivity or dielectric loss due to the conversion of electrical energy into thermal energy (dielectric loss factor), μ' gives stored magnetic energy and μ'' is related to the material loss. Food components, on the other hand, have little effect on the magnetic field; as a result, their key determinants are dielectric constant i.e. ϵ' , and loss factor i.e. ϵ'' respectively. Microwave propagation has been demonstrated to be sensitive to food freshness and deterioration. When using an electromagnetic measurement device to assess food quality, the variation of permittivity reflects food degradation. The sensor system is utilized to produce electric data that is then used to assess the food's moisture content, level of contamination, freshness, and material composition²¹. As the water and milk are the important component of food, these are chosen for the analysis.

3 Results and Discussion

3.1 Analysis of water quality

To analyze the water quality, samples of bore well water, tube well water, RO water, DI water, rainwater,

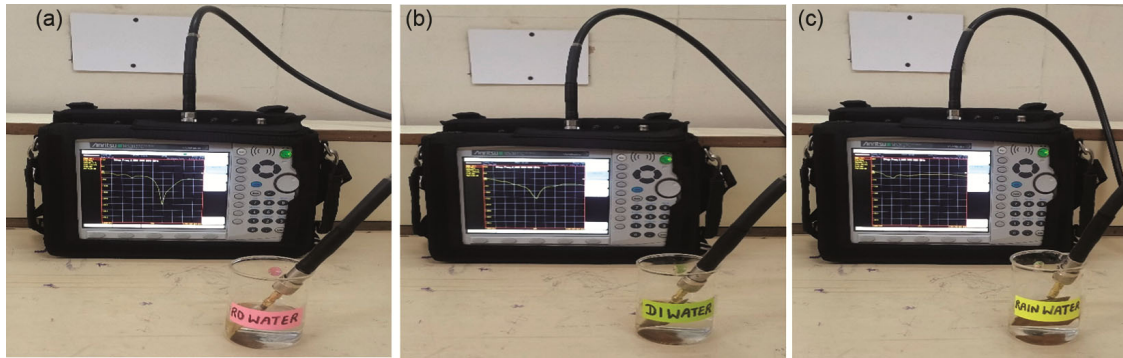


Fig. 5 — (a) RO (b) DI and (c) Rain water samples measurement setup.

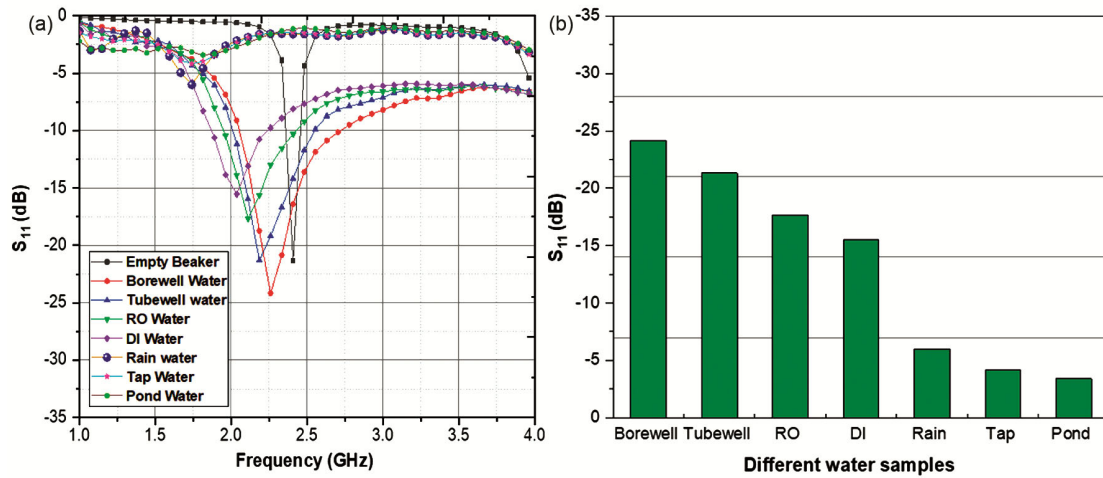


Fig. 6 — (a) Return loss for various water samples and (b) Corresponding reflection coefficient shift.

tap water, and pond water were taken. Figure 5(a, b & c) depict the measurement setup for analyzing the quality of RO, DI, and rainwater respectively. Each of the water samples appears to be clear and identical to the naked eye. The antenna sensor connected to the network analyzer can distinguish between return loss characteristics for the different types of water. The return loss properties of the antenna in the aqueous medium were affected by water factors such as dissolved ion concentration, conductivity, pH, and TDS. Consequently, the study of return loss features will give us a lot of information on water quality. Figure 6(a) provides the return loss of the antenna evaluated in various samples of water. For bore well water return loss is -24.18 dB, for tube well water is -21.32 dB, and for RO and DI water its values are -17.67 dB and -15.54 dB respectively. As the quality of water deteriorates, return loss shifts upward as for rainwater, tap water, and pond water return loss is -5.99 dB, -4.17 dB, and -3.40 dB respectively. It can be analyzed from the return loss graph that the quality of the water used for drinking

degrades as the return loss shifts upward. The difference in reflection coefficient for several samples of water can be observed in Fig. 6(b). The resonant frequency and reflection coefficient for the various samples are displayed in Table 2.

3.2 Analysis of milk quality

This section will evaluate the effectiveness of the antenna as a liquid milk sensor. For measurement, 100ml of buffalo pure milk was first stored at room temperature. The sensor was then submerged in a 100 ml milk sample to detect the fluctuation in return loss in accordance with frequency by using a VNA. The next step was to make distinct solutions from the sample of milk with various degrees of adulteration (or concentrations) to study the different cases, including (i) adulterating milk with water, (ii) adulterating milk with caustic soda, (iii) adulterating milk with sodium carbonate, (iv) adulterating milk with ammonium sulphate, and (v) adulterating milk with urea. The sensor has been immersed in the solution for around 2 minutes to achieve a steady

condition. Then, the VNA was used to measure the variation in return loss with regard to frequency. After each measurement, which was performed out at 25 °C room temperature, the sensor had been washed with tap water and dried using tissue paper. Finally, comparing graphs for pure samples of milk with solutions of various adulterants at varying levels of adulteration have been developed based on the results.

The observed reflection coefficients for pure buffalo milk and pure water samples are shown in Fig. 7(a). The experimental process of employing a microwave antenna as a sensor is shown in Fig. 7(b). The resonance frequency for buffalo milk is 2.04 GHz having a return loss of -17.24 dB, whereas for pure water, it is 2.04 GHz along with a value of -33.33 dB return loss.

3.3 Sensitivity analysis

A pure sample of buffalo milk was considered for the experiment. The relationship between resonance frequency variation and relative permittivity is expressed by the following equation²²:

$$\epsilon_r = \frac{-1}{0.19083} \ln \left(\frac{\Delta f - 1.75477}{-2.10315} \right) \quad \dots(7)$$

Table 2 — Reflection coefficient values for the various samples.

Different samples	Frequency (GHz)	Reflection coefficient (dB)
Empty beaker	2.41	-21.34
Bore well water	2.26	-24.18
Tube well water	2.19	-21.32
RO water	2.11	-17.67
DI water	2.04	-15.54
Rain water	1.74	-5.99
Tap water	1.74	-4.17
Pond water	1.81	-3.40

Where $\Delta f = f_r - f_0$ (f_r gives the frequency of resonance for the sensor, and f_0 represents the sensor's resonance frequency with the milk sample). The sensor's measured resonance frequency is 2.41 GHz. The sensor's observed resonance frequency with a sample of buffalo milk is 2.04 GHz. For the buffalo milk sample, the extracted value of permittivity is 2.2 as calculated by using Eqn (7) and the NS (numerical sensitivity) is 15.35% as given by⁴.

3.4 Estimation of milk adulteration

Adulteration estimation is generally a difficult task. This was accomplished by conducting tests on pure samples containing various adulterants to assess the sensitivity and accuracy of the proposed sensor¹⁸⁻²³. To detect the variation in return loss and resonant frequency, several adulterants (including water, caustic soda, sodium carbonate, ammonium sulphate, and urea) were given to a sample of pure milk. Depending on how much adulterant was added to the pure sample, the adulteration resulted in a frequency change and a shift in the reflection coefficient.

3.4.1 Case (i): Adulterating milk with water

To make milk more volumetric, water has been added. Even while the external addition of water to milk has no health risks if the water is free of pollution, doing so lowers the milk's nutritional value. Total Solid-Not-Fat (SNF) contents is one of the major factors in determining the quality of milk. Five separate samples were formed for this case study by mixing various volumes of water with milk. A 100 ml

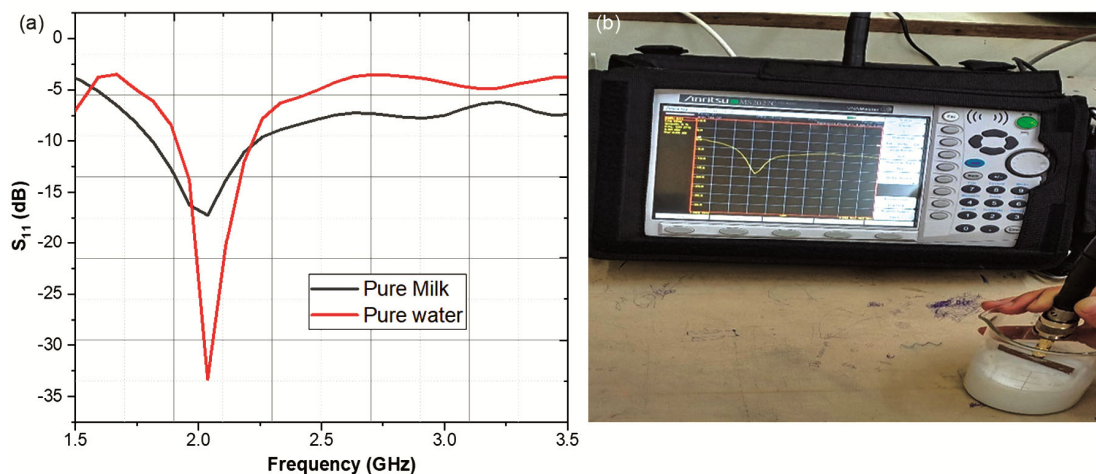


Fig. 7 — (a) Return loss measurement for a pure sample of buffalo milk and pure water and (b) Experimental arrangement using a microwave sensor for measurements.

pure milk sample was used in this investigation. With varying quantities of adulterants, several binary mixtures totaling 100 ml in volume were made. For example, 100 ml of milk, which was considered to be a pure milk sample, and 0 ml of water, which was considered to be an adulterant, were combined in a way that the total volume remained 100 ml. Then, gradually adding 10 ml of water to 90 ml of milk, the total volume remained 100 ml, and so on. In addition to ions and organic components including proteins,

lipids, carbohydrates, and vitamins, water is the milk's most significant chemical constituent. Ionic conduction losses in milk are caused by ions and are inversely correlated with frequency. When the water content in milk rises, it increases the dilution. Hence, the resonant frequency and reflection coefficient shift downside. Figure 8(a) displays the reflection coefficients for buffalo milk that has been contaminated with various quantities of water, using the reference sample of pure milk. It demonstrates

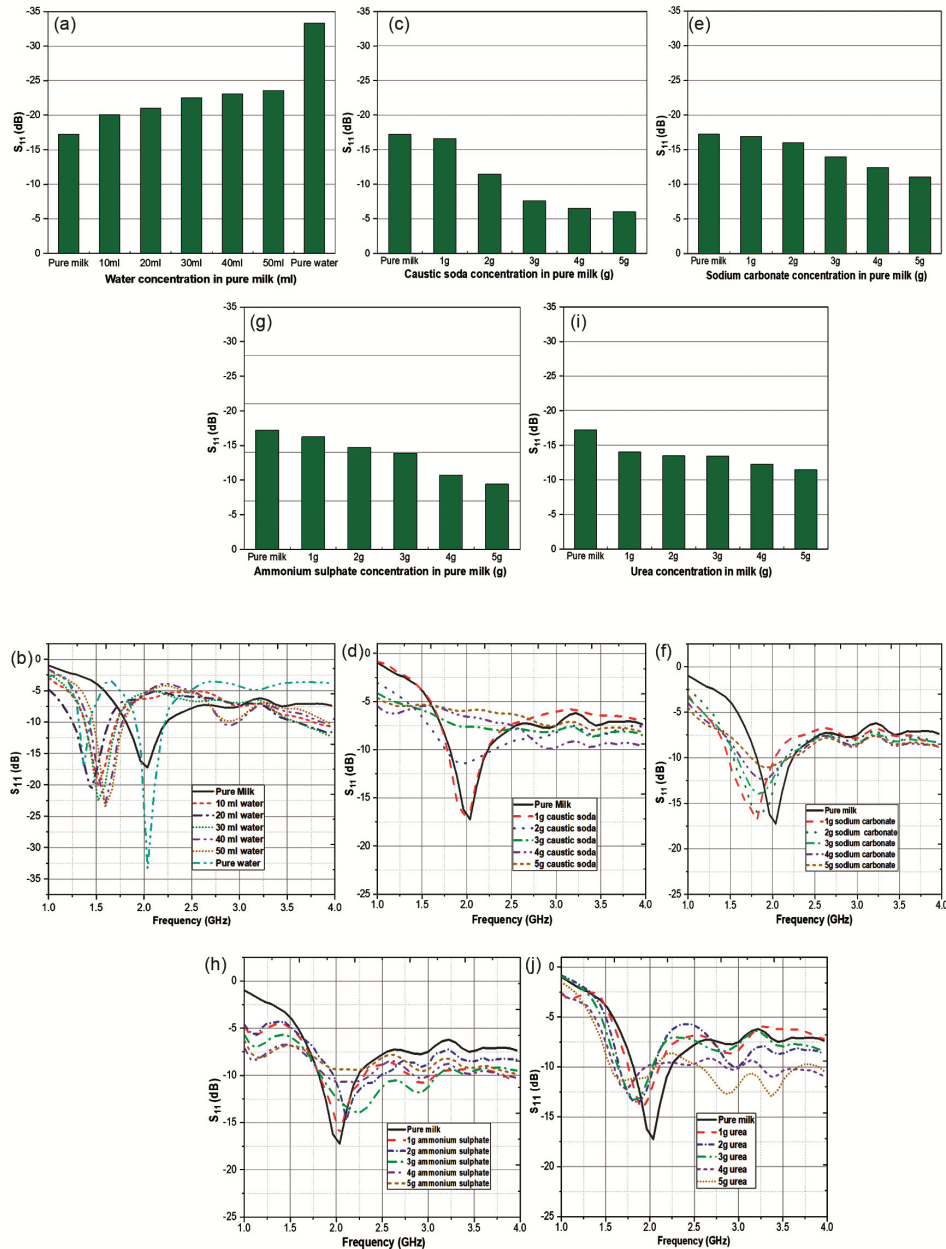


Fig. 8 — (a, c, e, g, i) Sensor responses for different adulteration levels of (a) water, (c) caustic soda, (e) sodium carbonate, (g) ammonium sulphate and (i) urea in pure buffalo milk. (b, d, f, h, j) Corresponding shift in return loss with different concentrations of adulterant in pure milk.

that the reflection coefficient for 10 ml of water in milk is -20.05 dB, for 20 ml -21.02 dB, for 30 ml -22.54 dB, for 40 ml -23.07 dB, and for 50 ml of water in milk is -23.59 dB respectively, while the reflection coefficient is -17.23 dB for pure milk and -33.33 dB for pure water. Thus, it may be concluded from Figures 8(a & b) that the return loss moves towards the downside when the amount of adulterant (in this example, water) increases in a pure milk sample, which is caused by the variation in the dielectric characteristics of different samples.

3.4.2 Case (ii): Adulterating milk with caustic soda

This section looks at milk adulteration using caustic soda, which is occasionally mixed with milk to enhance the shelf life of milk. Additionally, adding caustic soda is exceedingly dangerous. In children, it mostly destroys the mucosa of food pipes. In a pure sample of buffalo milk, five distinct degrees of adulteration were formed, with adulterant concentrations ranging from 1 to 5 g. The various milk samples were mixed with the caustic soda and let stand for five minutes to reach equilibrium. The dielectric constant, ϵ' varies with the amount of adulteration, which affects the resonant frequency and return loss values. Concerning the changing amounts of adulteration, the reflection coefficient shifts upward as the amount of the adulterant (in this case, caustic soda) rises in the solution, yielding values of -16.81 dB, -11.44 dB, -7.64 dB, -6.54 dB, and -5.99 dB. Figures 8(c & d) show that the return loss shifts upside when the adulterant content (caustic soda) rises in the pure samples of milk causing a shift in resonance frequency.

3.4.3 Case (iii): Adulterating milk with sodium carbonate

Gastric issues, such as peptic ulcers, colon ulcers, diarrhea, and electrolyte disturbances, are brought on by carbonate in milk. To increase the volume of the milk, sodium carbonate is typically added to adulterate raw milk. The quality of pure milk deteriorates as the adulterant content rises, posing major health risks. So monitoring milk quality is a key subject of concern. For the experimental setup, several samples were made utilizing buffalo milk samples with sodium carbonate concentrations ranging from 1 to 5 grams. Changes in composition and saturation level occur when the amount of sodium carbonate rises in pure milk. Figures 8(e & f) demonstrate that the return loss moves towards the upper side as the quantity of sodium carbonate in the pure milk rises, giving values of -16.92 dB, -15.97

dB, -13.96 dB, -12.43 dB, and -11.05 dB return loss for various amounts of adulterant in pure milk.

3.4.4 Case (iv): Adulterating milk with ammonium sulphate

The inappropriate addition of ammonium sulphate to milk to maintain the required density has also been noted as a milk adulterant. The lactometer level is increased while the density of diluted milk is maintained using ammonium sulphate. For testing, a clean sample of buffalo milk was treated with ammonium sulphate to create five various degrees of adulteration, ranging from 1 to 5 g. The milk sample was mixed with ammonium sulphate, and then let to stand for five minutes to reach equilibrium. It was found that the dielectric characteristics of the solution vary as the proportion of adulteration rises. The resonant frequency is shifted and the reflection coefficient changes as a result of the altered dielectric constant. Figure 8(g) illustrates how the content of ammonium sulphate in pure buffalo milk changes the reflection coefficient. The reflection coefficient shifts upper side with increasing adulterant content in the solution, providing values of -16.23 dB, -14.71 dB, -13.91 dB, -10.69 dB, and -9.40 dB about varied adulteration levels. Figures 8(g & h) show that the dielectric constant changes as the amount of adulterant (ammonium sulphate) rises in the pure milk samples, causing an upward shift in return loss and a change in the frequency of resonance.

3.4.5 Case (v): Adulterating milk with urea

Urea, a component of milk that occurs naturally, makes up the bulk of the non-protein nitrogen in milk. Commercial urea is introduced into milk to increase its non-protein nitrogen concentration. It gives milk whiteness, boosts consistency, and enhances SNF in milk to resemble genuine milk. For testing, urea was added to a clean sample of buffalo milk to create five distinct levels of adulteration, ranging from 1 to 5 g. The milk sample was mixed with the urea, and then let to stand for 5 min to reach equilibrium. It was found that the dielectric characteristics of the solution vary as the proportion of adulteration rises, hence the resonant frequency is shifted and the reflection coefficient moves to the upper side. The fluctuation in the reflection coefficient with increasing urea content levels in pure buffalo milk is seen in Fig. 8(i). Concerning the variable adulteration level, the reflection coefficient shifts upside as the adulterant concentration in the solution rises, yielding values of -14.06 dB, -13.49 dB, -13.43 dB, -12.28 dB and -11.44 dB. Figures 8(i & j) demonstrate that when the

amount of adulterant (urea) in the pure samples of milk rises, the dielectric constant changes, showing a shift in the return loss and a change in the frequency of resonance. The experimental findings regarding a shift in reflection coefficient with various adulteration amounts are presented in Table 3. Table 4 presents the results of a comparison between our proposed work and the previously published microwave sensors for liquid determination. Due to its submersible feature

and small size, the suggested sensor also clearly outperforms existing sensors.

4 Conclusion

The proposed antenna sensor is utilized to evaluate the quality of milk and other water samples. A network analyzer has been used to test the reflection coefficient of the antenna sensor under various water samples and adulterated milk. The upward shift in the reflection coefficient can be related to a drop in drinking water quality. As a result, it is determined that the water may be appropriate for drinking if the return loss is less than -15 dB. The experimental findings for identifying adulteration in a milk sample clearly demonstrate that as adulteration level rise, the composition and saturation level of solution changes. This leads to a change in the permittivity of the solution, which causes variations in return loss and resonant frequency. When water is used as an adulterant in milk then the return loss shifts downward due to increase in dilution. As other adulterants like caustic soda, sodium carbonate, ammonium sulphate, and urea are added to milk, the return loss shifts towards the upside as the quantity of adulterant rise. Thus the return loss values provide us the information about the quality of the liquid under test. A low-cost microwave sensor operating at 2.4 GHz frequency is presented and tested. The single-port microwave sensor was created using low-cost PCB (printed circuit board) technology and is incredibly easy to use, small, affordable, and capable of being immediately submerged in the liquid being tested. Thus suggested antenna sensor is very valuable for liquid quality analysis and WLAN applications.

Table 3 — Results from experiments showing how the reflection coefficient varies with the extent of adulteration.

Adulterant	Quantity	Reflection coefficient (dB)
Water	10 ml	-20.05
	20 ml	-21.02
	30 ml	-22.54
	40 ml	-23.07
	50 ml	-23.59
Caustic soda	1 g	-16.81
	2 g	-11.44
	3 g	-7.64
	4 g	-6.54
	5 g	-5.99
Sodium carbonate	1 g	-16.92
	2 g	-15.97
	3 g	-13.96
	4 g	-12.43
	5 g	-11.05
Ammonium sulphate	1 g	-16.23
	2 g	-14.71
	3 g	-13.91
	4 g	-10.69
	5 g	-9.40
Urea	1 g	-14.06
	2 g	-13.49
	3 g	-13.43
	4 g	-12.28
	5 g	-11.44

Table 4 — Analyzing the antenna described here in comparison to previously published work.

Reference	Operating Frequency (GHz)	Dimension	Antenna Model	Q-factor	Limit of detection	Analyzed Parameters	Sensitivity (%)
24	6.9	80mm×80mm	AMC Array	69	10%, 4%	Water and Ethanol in Oil	—
25	3.4,5.8,6.2 and 8.9	50mm×50mm	Microstrip Sensor	—	20g	Salt and sugar in water	—
26	2.45	111mm×111mm	EBG structure	12.81	—	Liquid permittivity's	4
27	1.62	78mm×50mm	(MCSRR) Structure	25.6	—	Liquid permittivity's	0.76
28	2.5	—	Meta material	42	50ppm	Ethanol/Methanol Concentrations in water	0.27
29	1	86mm×62mm	SRR	—	—	Dielectric Characterization of Liquids	0.195
This work	2.4	35mm×43mm	CSRR	60.25	10ml, 1g	Water quality, Adulteration of milk	0.42

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