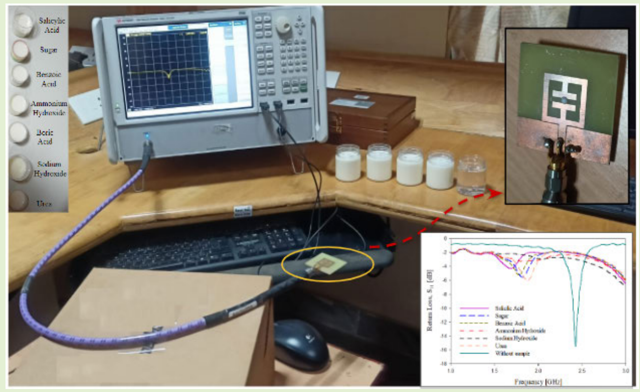
A Novel Microstrip Sensor Based on Closed Loop Antenna for Adulteration Detection of Liquid Samples

S. Aiswarya, L. Meenu, K. A. Unnikrishna Menon, Massimo Donelli, *Senior Member, IEEE*, and Sreedevi K. Menon

***Abstract*—The design, development, and analysis of a planar microstrip sensor operating at 2.4 GHz for the detection of adulteration in liquid samples is presented. The sensor characterizes the samples based on the material properties which in turn affects the electric field fringing from the sensing area. In particular, a closed loop microstrip antenna is developed and used for the sensing application. The sensor is designed and analyzed using simulation software and the fabricated prototype is experimentally validated. Parametric analysis of the design variables and mathematical modeling of the sensor operations are carried out by analyzing the fields generated within the sensor. A case study for adulteration testing is carried out by choosing milk as the sample. Qualitative and quantitative testing using the milk as sample has been carried out experimentally under different test conditions. For quantitative testing, water is added to milk as the adulterant and for qualitative testing, usual chemical adulterants that are mixed with milk are added and the variations in operating frequency and return loss are analyzed. From the analysis, it could be observed that the shift in the operating frequency and return loss are dependent on the changes in dielectric permittivity of the sample loaded on to the sensor surface. From this analysis, the adulteration rate in milk can be estimated based on the variation in permittivity of the adulterant that is added to the milk. The same procedure can be extended in detecting the adulteration of any liquid samples.**



***Index Terms*— Adulteration, loop antenna, microstrip, microwave, sensor.**

I. Introduction

FOOD is one of the basic necessities for supporting life of all living creatures including human beings. The socio economic nature has lead to the demand of packaged food materials and this has led to the experimentation in increasing the shelf life of the products. To enhance the expiry period of the packaged foods, the use of adulterants which deceives the appearance and taste are used to make the food look alike and fresh. Food adulteration is one of the most serious problems the society is facing today. The main cause of many of the acute and chronic diseases is the intake of adulterated food products [1], [2], [3], [4], [5], [6], [7]. The continuous intake of even the small quantity of adulterant added to the food for preservation may lead to serious health disorders like nutritional deficiencies, different allergies, kidney disorders, heart diseases, failure of organ systems including heart, lungs, and liver [8], [9]. Adulteration in food is done in order to show the increase in quantity or to prevent contamination, to provide better shelf life. Anyway, for any case or cause, the final results may be sometimes life threatening [10], [11]. The adulteration in food products is higher in the developing countries compared to the developed countries due to the lack of cost effective and efficient technologies for detecting the rate of adulteration in food products [12], [13]. This work discusses the adulteration detection techniques for liquids and proposes a microwave sensing based adulteration detection system based on the variations in dielectric permittivity of the sample to be tested. As a case study for the liquid adulteration testing, milk is chosen as the liquid sample for testing.

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Milk is one of the naturally available food sources available for consumption [14], [15]. It has high nutritional benefits compared to other foods and is the primary food item of toddlers and kids for their growth [16], [17]. Majority of the canned and packed food items are byproducts of milk, some of which may be chocolates, curd, cheese, and butter or may contain any of these products [18], [19]. The main disadvantage of the milk and its products is that it becomes not suitable for consumption and creates adverse health issues if it is contaminated [20]. Adulteration in milk can be by either adding water into it for increasing the quantity or to add chemicals like urea, ammonium sulfate, boric acid, sodium hydroxide, sugar, salicylic acid, and benzoic acid on to the milk for compensating the water added without loosing the texture and appearance for increasing the shelf life [21], [22].

There are various methods for the detection of adulteration in milk products. The detection of adulteration in milk using different techniques like infrared spectroscopy, differential scanning calorimetry are discussed in [23]. Usual lab-based chemical test for detection of adulterants like sugar, starch, salt, etc. are presented in [24]. There are various methods for detection of adulteration in foods [25], [26]. Most common method is by using chemicals available in lab or by using test strips. The main disadvantage of these test strips are its high cost and their properties deteriorate with time and on reaction with the environment.

Planar microwave structures finds many applications in various domains [27], [28], [29]. The different applications using the planar microwave antenna as microwave sensors are discussed in [30], [31], [32], [33], [34], [35], [36], [37], and [38]. Based on theoretical and analytical procedures [39], antenna is developed and the sensing properties are practically tested in controlled environment. Adulteration detection by adding water and other chemicals into the milk in order to increase the shelf life contributing to health issues are discussed and proposed a technique for finding out the adulteration of milk. So, as a case study adulteration detection in milk using microwave sensor is presented in this article. This article proposes a system for adulteration detection in liquid samples, based on a microstrip loop antenna.

This article is organized as follows. Section II deals with the sensor design and development. Numerical assessment of the microstrip sensor using electromagnetic simulators is discussed in Section III. Section IV discusses the experimental testing for detecting the adulteration in milk. Finally, Section V concludes the work.

II. Sensor Design and Development

The development of a planar microwave sensor is proceeded through a series of process which involves both simulation and experimental studies based upon the application. A block diagram that illustrates the flow of design and process in developing an adulteration detection sensor is shown in Fig. 1.

A. Theoretical Design With Simulation Analysis

The development of a microstrip closed loop antenna (MCLA) sensor begins with the design of coplanar waveguide (CPW) and the design flow is shown in Fig. 2. A CPW structure consists of three metallic planes on the top of dielectric plate, out of which central pole is the radiating element and the other two metallic planes on either sides of the radiating element are the symmetric ground planes. This structure operates as an ultra wide band monopole antenna with low Q. In order to improve the Q factor of the structure, square loop and two open end stubs are added as shown in Fig. 3. A comparison on the performance of the proposed antenna from the basic antenna designs optimized for 2.48 GHz is reported in Table I.

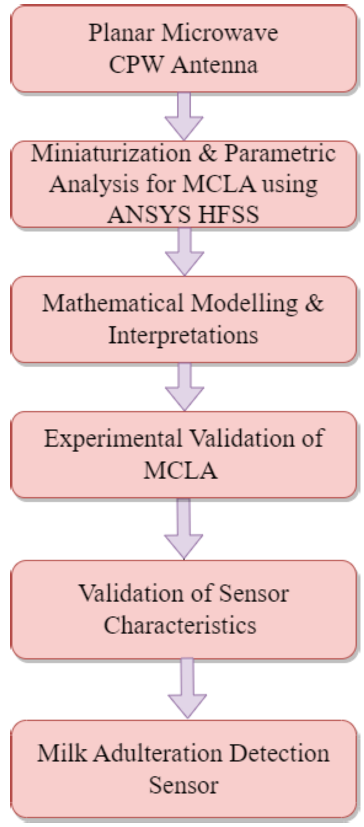

Fig. 1. Block diagram of flow of processes.

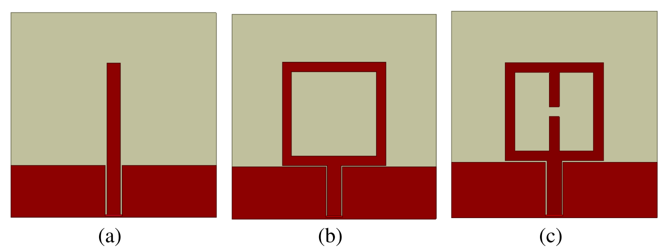

Fig. 2. CPW fed antenna to MCLA design. (a) CPW antenna. (b) CPW loop antenna. (c) CPW loop antenna with stubs.

So, the square loop CPW with T shaped stubs antenna—MCLA is chosen as the final design and the parametric analysis of the same is carried out using electromagnetic simulator. A circuit equivalent of the proposed MCLA is developed after doing the necessary analysis based on referring to the related works in the area [40]. The developed equivalent circuit is shown in Fig. 4. In the figure, Z_{in} is the input impedance, C_r is the input capacitance, R_r is the radiation

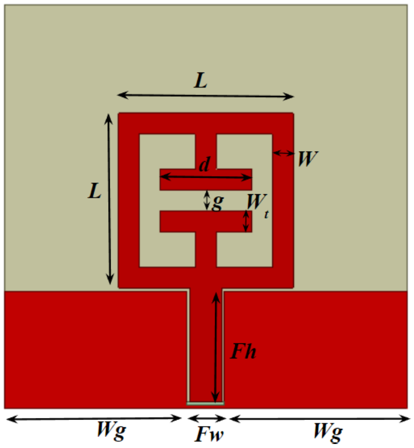

Fig. 3. Proposed MCLA.

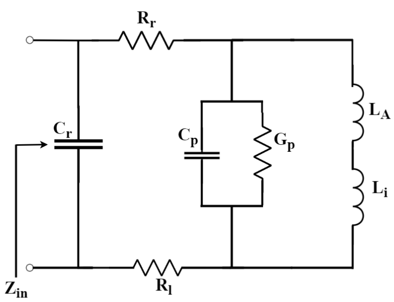

Fig. 4. Equivalent circuit of proposed MCLA.

TABLE I
COMPARISON OF CPW ANTENNAS OPTIMIZED AT 2.48 GHz

Antenna type	**Bandwidth [GHz]**	**Gain [dB]**	**Q factor**	**Overall size [mm2]**
CPW Antenna	0.315	1.81	7.8	1980
Square Loop CPW Antenna	0.4	2.35	6	1980
Square Loop CPW with I stubs Antenna	0.3	2.24	8	1764
MCLA	0.12	1.85	20	1505

resistance, R_L is the resistance of loop antenna, C_p is the capacitance of the parallel stub, G_p is the conductance of the parallel stub, L_A is the inductance of the loop, and L_i is the inductance of the loop conductor.

The parametric analysis of the dimensions of MCLA like length of loop, "L," width of loop, "W," length of the parallel stub, "p," width of parallel stub, "W_t" and gap between the parallel stubs "S" are carried out and the variation in each of these parameters with respect to frequency is analyzed and is shown in Fig. 5.

From the analysis, it is observed that the parameters like length of loop, "L," width of loop, "W," width of parallel stub "W_t" and gap between the parallel stubs "S" have an inverse relationship with frequency whereas length of the parallel stub, "p" have a direct relationship with frequency.

On basis of the analysis and considering the dielectric permittivity and micro strip feed characteristics, the dependency and relation between the analyzed parameters and frequency is

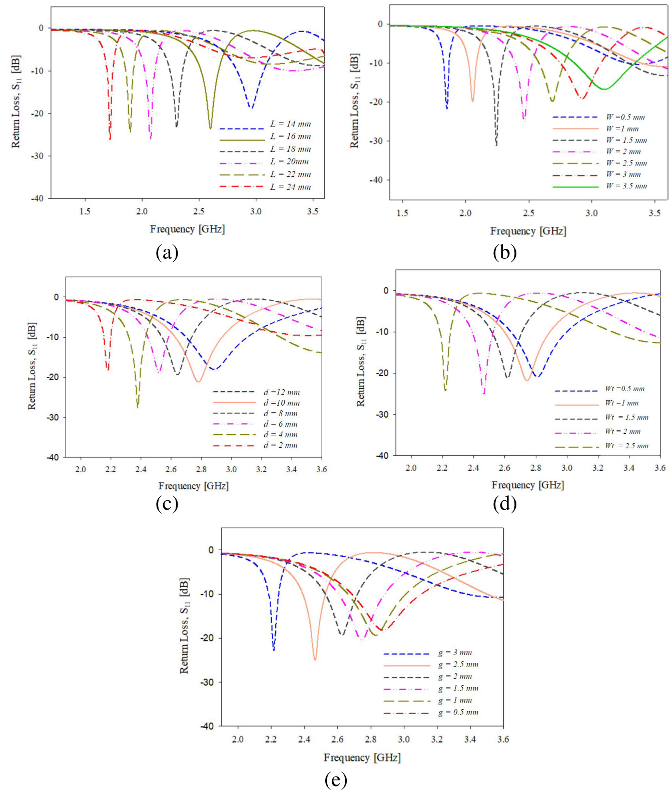

Fig. 5. Parametric analysis. (a) Variation of side length of square loop, L with frequency. (b) Variation of width of square loop, W with frequency. (c) Variation of length of parallel stub. d with frequency. (d) Variation of width of parallel stub, W_t with frequency. (e) Variation of gap between the parallel stubs g with frequency.

derived. Using a proportionality constant which is a function of dielectric permittivity, an empirical mathematical model of the design is developed for predicting the operating frequency if the dimensions of the design are known. The derived mathematical equation for the designed antenna using the parametric variables is given in

$$f_w = \frac{\gamma C g W \sqrt{\frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2\sqrt{1+\frac{12h}{w}}}}}{2LW_t d} \tag{1}$$

where γ is an empirical weighting factor which depends on the substrate dielectric permittivity. In particular, $\gamma = 0.0041$ for $3.2 \leq \varepsilon_r < 4.0$, $\gamma = 0.00332$ for $4.0 \leq \varepsilon_r < 6.0$, $\gamma = 0.00269$ for $6.0 \leq \varepsilon_r < 8$, and $\gamma = 0.001873$ for $8 \leq \varepsilon_r < 9.2$. The validation of the designed empirical equation using electromagnetic simulator is done in Rogers-TM-based substrates and an error less than 8% for other lossy dielectric materials is observed. The validation results is shown in Fig. 6.

B. Experimental Assessment

As can be noticed from the data reported in Table I, the introduction of the square loop and the two open stubs improves the quality factor of the structure from 7.8 up to 20. The overall size of the designed sensor is 38.8 × 38.8 × 1.6 mm. The dimensions of each of the design parameters as represented in Fig. 3 is shown in Table II. The structure

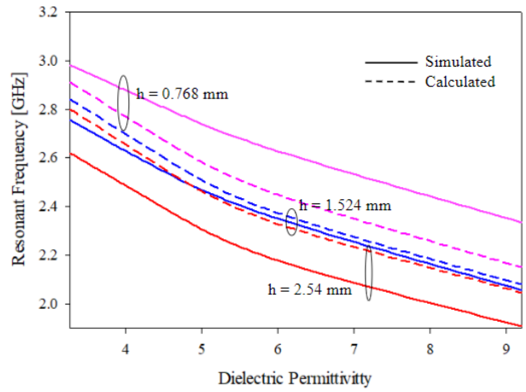

Fig. 6. Validation of the empirical relation.

TABLE II
DIMENSIONS OF THE DESIGNED MCLA

Design Parameters	Dimension [mm]
Side of the square loop, L	16.8
Width of the square loop, W	2
Length of the parallel stub, d	8.8
Width of the parallel stub, W_t	2
Gap between the the parallel stub, g	2
Length of the rectangular ground, Wg	17.6
Width of the rectangular ground, Fh	11

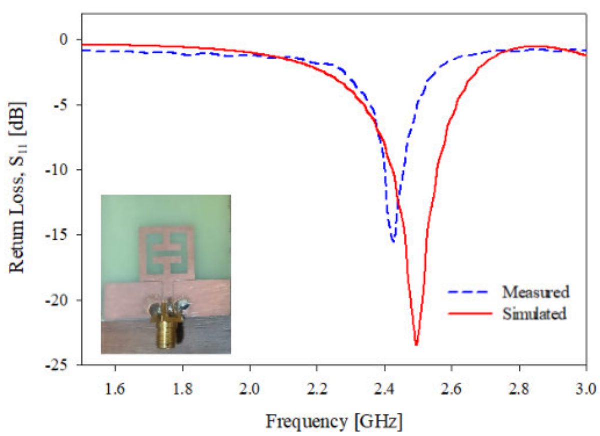

Fig. 7. Return loss of MCLA.

reported in Fig. 2 is simulated with ANSYS Electronics Desktop 2022—HFSS Design in FR4 epoxy substrate having dielectric permittivity 4.4 and loss tangent 0.02.

An experimental prototype is fabricated on FR4 epoxy substrate and experimentally validated using E5080A Vector Network Analyser. The variation in return loss, S_{11} with frequency is shown in Fig. 7. In the figure there is a shift in frequency between the measured and simulated results due to fabrication errors. The sensor radiates an electromagnetic field with omnidirectional radiation pattern with an average gain of 1.85 dBi. The radiation pattern and gain characteristics are reported in Figs. 8 and 9, respectively. The radiation pattern and gain of the antenna has an impact on the sensing operation depending upon the dielectric permittivity of the sample loaded on to the sensor.

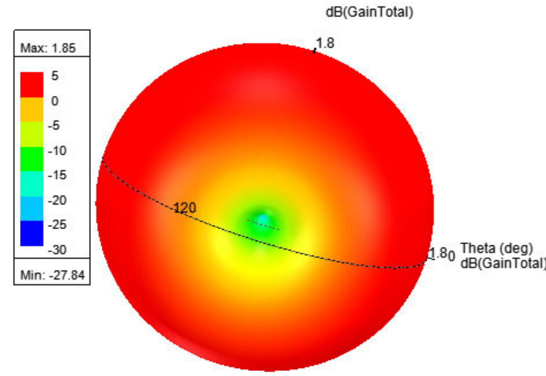

Fig. 8. Gain of antenna.

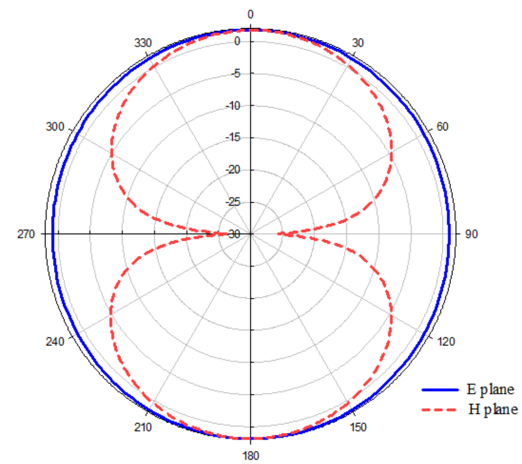

Fig. 9. Radiation pattern.

The simulation and experimental analyzing and testing of MCLA as a liquid adulteration detection sensor is discussed in the next sections. By using the Fraunhofer equation, the near and far-field boundary is calculated and all the sensor testings are done in the near-field of the antenna.

III. SIMULATION ANALYSIS: MCLA AS A MICROWAVE SENSOR

In this section, the sensing capabilities of the proposed sensor are numerically assessed by using a commercial numerical software namely HFSS. For the analysis, a hemispherical structure is designed and placed on to the MCLA sensor and the optimization of the loading position and the size of the liquid sample is carried out for optimizing the sensing location and maximize the sensing capabilities of the sensor. Fig. 10 represents the simulation setup of the antenna with the sensing element loaded on to the top of the area having maximum sensitivity. The simulation analysis on analyzing the electric and magnetic fields, physical dimension of the sample loaded on to the sensor and the sensitivity analysis is discussed in detail in the following sections.

A. Theory of Sensing

In general, a planar microwave antenna could act as a sensor depending upon the interaction between the material properties of the samples loaded and electromagnetic waves. The sensing

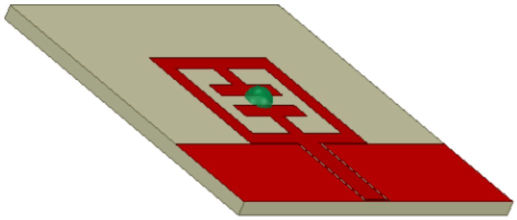

Fig. 10. Simulation setup for testing antenna as a sensor.

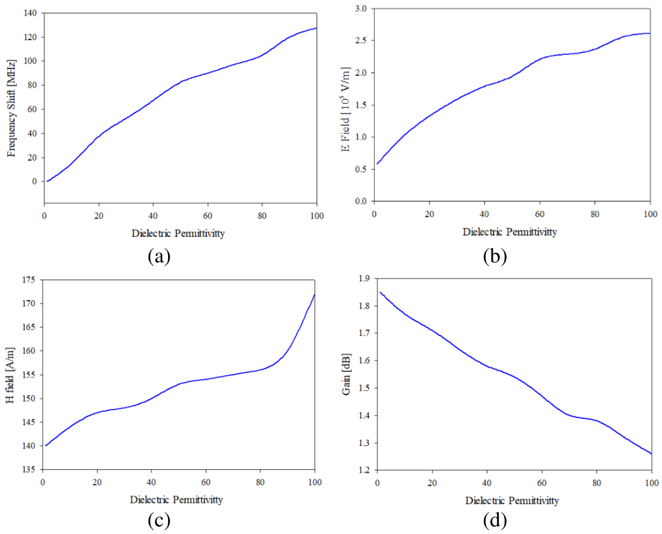

Fig. 11. Influence of dielectric permittivity of the loaded sample in antenna properties. (a) Frequency. (b) *E* field. (c) *H* field. (d) Gain.

operation is due to the change in dielectric permittivity at the capacitive area where the material is loaded on to the sensor based on (2) [33]

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{2}$$

where C is the capacitance, ε_0 is the permittivity of free space, ε_r is the relative permittivity due to substrate and loaded liquid sample, and A is the sensing area. This capacitance is dependent on the permittivity and is also dependent on the field existing in the sensor. The dielectric permittivity of the material is having either direct or indirect influence in all the sensor properties. The influence on dielectric permittivity of loaded sample on to the frequency, E field, H field, and gain of the antenna are analyzed and is shown in Fig. 11.

B. Field Analysis

The sensitivity of the sensor is directly dependent on the field distribution around the excited sensor. In order to find out the region having maximum field intensity, the electric and magnetic field distribution of the sensor without loading any samples is taken and is shown in Figs. 12 and 13.

From Fig. 12, it could be observed that the maximum field is being concentrated in between the parallel stubs. At the tip of the parallel stubs, we could see maximum electric field. The capacitive effect at the tip of the stubs had lead to maximum concentration of electric field at these points which contributed to the maximum sensitivity at the same points.

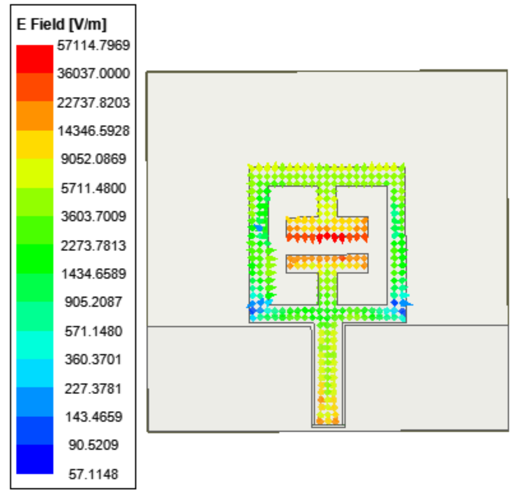

Fig. 12. Electric field of the antenna.

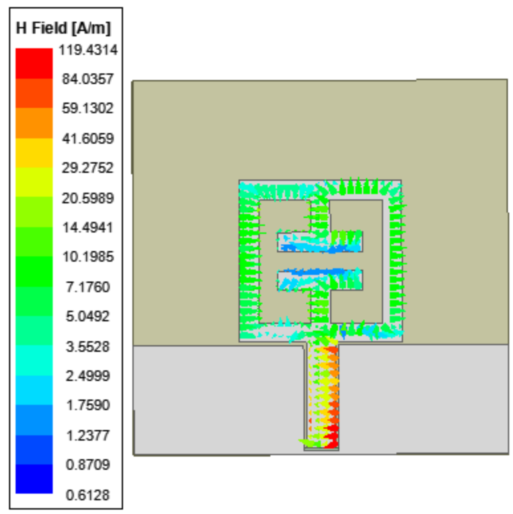

Fig. 13. Magnetic field of the antenna.

Considering all the factors, we could conclude that the area having maximum electric field concentration within the antenna is the area having maximum sensitivity.

Consider the fields generated case when sample is loaded on to the sensor. The electric field and magnetic field generated in this case is shown in Figs. 14 and 15, respectively.

The ratio of electric field and magnetic field when an electromagnetic wave is traveling from one medium to another is generally known as intrinsic impedance or wave impedance.

On solving the wave equation the intrinsic impedance is given by

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}}. \tag{3}$$

In (3), η is the intrinsic impedance, ω is the angular frequency, μ is the permeability, and ϵ is the permittivity. On expanding μ and ϵ in

$$\eta = \sqrt{\frac{j\omega\mu_0\mu_r}{\sigma + j\omega\epsilon_0\epsilon_r}} \tag{4}$$

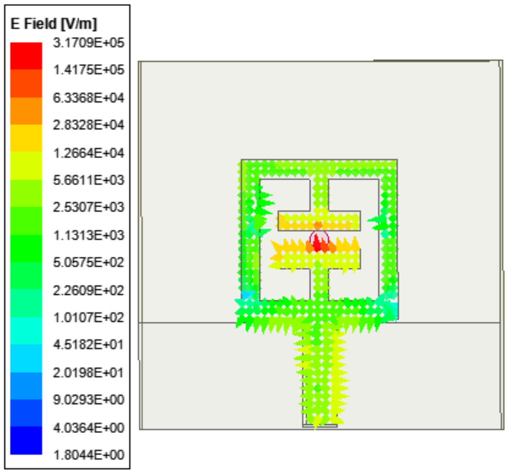

Fig. 14. Electric field generated in antenna with sensor loaded.

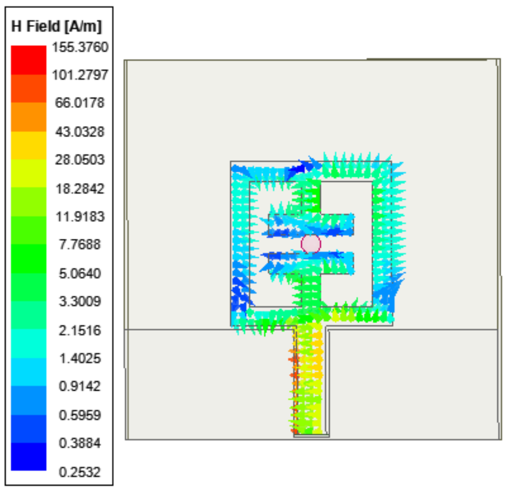

Fig. 15. Magnetic field generated in antenna with sensor loaded.

where μ_0 and ϵ_0 are the permeability and permittivity of free space and μ_r and ϵ_r are the permeability and permittivity of the medium in which electromagnetic wave propagates, here it is within the sensor, between the parallel stubs.

Comparing the fields generated without and with sample having the dielectric permittivity of pure milk, $\epsilon_r = 57.7$ loaded on to the sensor, it could be observed that the electric field has increased 5.5× and magnetic field has increased 1.3×, especially in the region that has maximum electric field and least magnetic field concentrates. This field variation is dependent on the material properties of the loaded samples on to the sensor.

C. Physical Dimension of Sample

The size of the drop of sample loaded onto the sensor is increased and the corresponding variation in operating frequency has been measured and is shown in Fig. 16.

D. Sensitivity Analysis

Sensitivity of a sensor is the slope of the output characteristics curve or the minimum input value that could produce a considerable change in the output side. Here the parameters

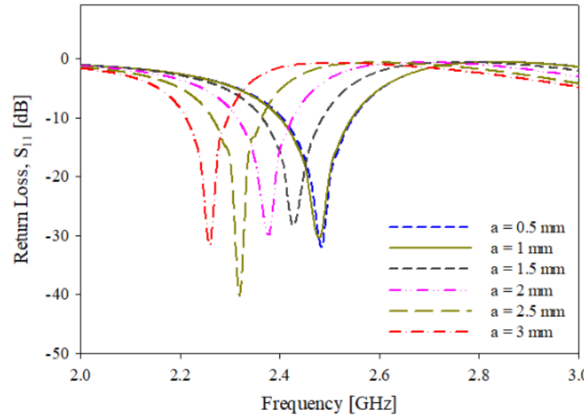

Fig. 16. Parametric analysis of size of drop: variation of radius of drop, "a" with frequency.

like the position of loading the sample, dielectric permittivity, conductivity and size of the sample loaded have an influence on the sensitivity of the developed sensor. Mathematically, sensitivity can be expressed as follows:

$$S_{\varepsilon_r} = \frac{\Delta f}{\Delta \varepsilon_r} = \frac{\Delta f \Delta E}{\Delta D} \quad (5)$$

$$S_{\text{sample size}} = \frac{\Delta f}{\Delta a} \quad (6)$$

where S_{ε_r} is the sensitivity with respect to change in dielectric permittivity, $S_{\text{sample size}}$ is the sensitivity with respect to change in sample size, Δf is the change in operating frequency, $\Delta \varepsilon_r$ is the change in dielectric permittivity, and Δa is the change in sample size.

Normalized sensitivity [41] can be expressed as follows:

$$Sn_{\varepsilon_r} = \frac{\Delta f}{f_0 \Delta \varepsilon_r} \quad (7)$$

$$Sn_{\text{sample size}} = \frac{\Delta f}{f_0 \Delta a}. \quad (8)$$

IV. Experiments: Adulteration Testing in Milk

In the following sections, the proposed sensor is experimentally assessed. The testing of the designed MCLA sensor for adulteration detection of liquid samples is presented in this section. As a case study, milk is chosen as the sample for testing adulteration. The experimental study of adulteration testing in milk using water and chemicals is discussed below.

A. Water as Adulterant

The adulteration testing in milk using water is demonstrated experimentally in lab environment and the results are analyzed. Varying measured quantities of water are added to milk as adulterant and the variation in operating frequency and return loss are observed. Five different concentrations of milk and water like, 100% milk (Milk:Water::4:0), 75% milk and 25% water (Milk:Water::3:1), 25% milk and 50% water (Milk:Water::2:2), 25% milk and 75% water (Milk:Water::1:3), and 100% water (Milk:Water::0:4) are taken for testing. The samples are prepared in separate beakers and are stirred uniformly so as to get a uniform solution.

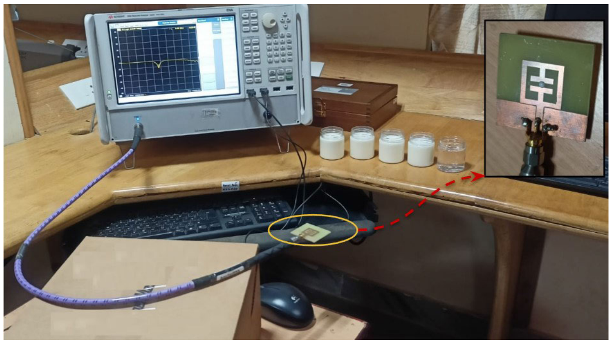

Fig. 17. Measurement setup.

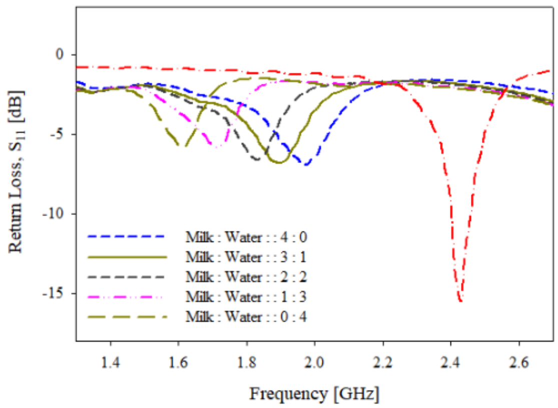

Fig. 18. Variation in operating frequency and S_{11} for different concentrations of water added on to milk.

From the prepared mixtures, a measured quantity, 50 μL of the same in the shape of a drop, hemispherical similar to that in simulation, is placed on the region having maximum electric field or the sensing area and the influence of the same on antenna characteristics is noted. The test setup of the experiment is shown in Fig. 17. On adding the test samples onto the sensor, the operating frequency and return loss are getting shifted depending upon the concentration and material properties of the adulterant within the sample loaded onto the sensor. Fig. 18 shows the variation in operating frequency and return loss for various concentrations of milk. From the analysis results, the quantity of water that is added as an adulterant to milk can be calculated. The variation in the dielectric permittivity of the sample leads to the variation in operating frequency and return loss. The variation in frequency shift and return loss with respect to operating frequency values for increasing percentage of adulteration is shown in Fig. 19. From the graph, it could be clearly observed that the frequency shift and return loss have a direct dependence with the increase in the rate of adulteration.

B. Chemicals as Adulterant

In order to increase the shelf life, different adulterants are added to milk. In this experimental testing, different harmful chemicals that are usually added to milk for adulteration purposes are mixed into pure milk. In particular, 50 μg of chemicals like urea, sodium hydroxide, boric acid, ammonium hydroxide, sugar, and salicylic acid are added to 10 mL milk.

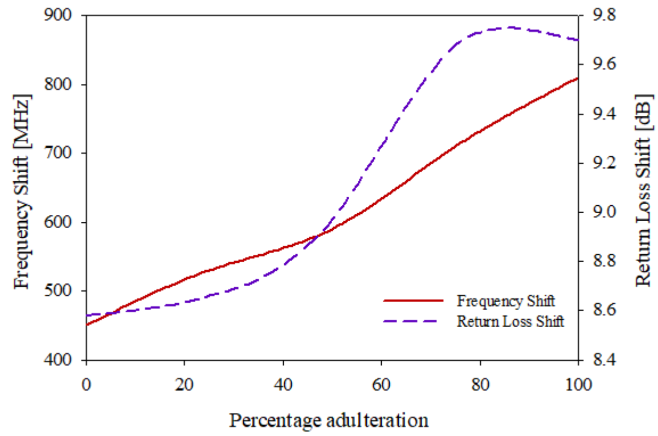

Fig. 19. Percentage adulteration.

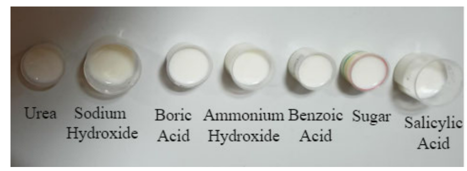

Fig. 20. Chemical samples added as adulterants.

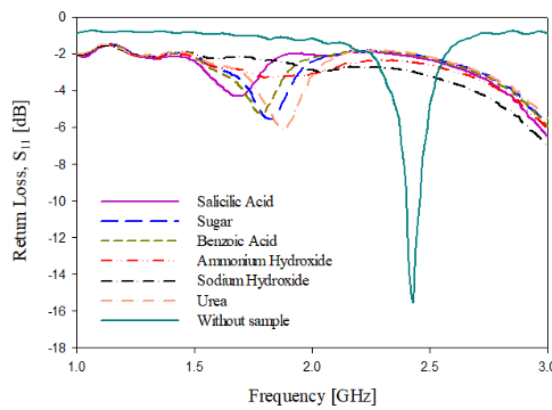

Fig. 21. Variation in operating frequency and S_{11} for different adulterants added on to milk.

The prepared mixtures are stirred well and then allowed to settle. These adulterated milk samples are shown in Fig. 20. 25 μL drop of the prepared mixture is loaded onto the sensor surface and the variations in return loss and operating frequency are analyzed.

As the permittivities of the prepared mixtures are different, the return loss variation with respect to frequency can be observed. Fig. 21 shows the variation of operating frequency and return loss for different adulterated milk samples with chemicals. As can be noticed from the data reported in Fig. 21, the effects of adulterants are quite evident. The depths of respective peaks are strongly reduced and shifted in frequency. In particular, more frequency shift occurs for salicylic acid, as it has the least value of dielectric permittivity. Similarly, the chemical having the highest value of permittivity produces the lowest frequency shift. This analysis provides clear evidence that the sensitivity of the sensor is dependent on the dielectric permittivity which in turn influences the operating frequency.

TABLE III
COMPARISON WITH EXISTING WORKS

Reference	Frequency (GHz)	Permittivity	Sensor	Contact	Sensor size (mm2)	Sample Size (uL)	Permittivity Range	Frequency Shift (MHz)	Normalised Sensitivity	Relative Sensitivity
This Work	2.48	4.4	Loop antenna	Yes	38.8*38.8	25	1-100	600	13.7	1109
Ref [42]	2.6	2.2	MTM	No	-	5	1-100	-	0.27	-
Ref [42]	2.6	2.2	OLR	No	-	5	1-100	-	-	-
Ref [43]	1.19	2.2	OLR	No	-	50000	-	-	-	-
Ref [44]	1.156	2.2	SRR	No	-	10	-	0.012	0.2	101
Ref [45]	1.51	-	CSRR	Yes	38*32	-	-	498.4	-	-
Ref [46]	2.3	2.2	CSRR	Yes	-	-	-	118	-	-
Ref [34]	2.4	3.66	LC	Yes	-	-	-	-	-	-
Ref [47]	2.48	3.66	RLC	No	-	-	8.22–79.5	920	-	-

C. Discussion

The performance of the sensor is dependent on different parameters such as operating frequency, bandwidth, response time, and sensitivity. Out of all these parameters, sensitivity has a lead role in determining the performance of the sensor.

The sensitivity of the developed sensor is calculated by analyzing the variation in the output parameter, i.e., shift in resonant frequency with respect to the input parameters like change in the size of sample loaded and change in dielectric permittivity. Each parameter is considered and the sensitivity is calculated separately.

From the data analyzed from the experiments using simulation and experimental testing, normalized and relative sensitivity of each case are calculated. The final average relative sensitivity is 1109 on varying dielectric permittivity. Similarly, the final average normalized sensitivity is 13.7 on varying sample size. The comparison of the designed sensor with the existing works is shown in Table III.

V. CONCLUSION

The development and sensing analysis of a planar microwave closed loop antenna sensor implemented on FR4 epoxy substrate for adulteration detection application is discussed in this work. The sensor is designed using a miniaturized CPW-fed ominidirectional antenna having gain of 1.8 dB having Q of 20. Each of the antenna characteristics has a significant role in developing the property as a sensor. The operational behavior, field analysis, and physical parameters have influence on the sensitivity characteristics of the designed MCLA sensor analyzed using simulation software. The sensing property of the antenna sensor is experimentally validated for adulteration detection of milk both quantitatively and qualitatively. The quantitative analysis with water as an adulterant to milk and qualitative analysis is performed by adding different chemicals as adulterants. For both analysis, the adulteration is identified by monitoring the variation in frequency and return loss depending on the permittivity of the sample under test. This variation in the operating frequency and return loss determines the percentage of adulteration. For milk adulteration testing average normalized sensitivity is 13.7 when varying the sample size. The average of normal sensitivity and relative sensitivity on varying the dielectric permittivity of the sample are 2.75 and 1109, respectively. The chemical adulteration testing also provided higher sensitivity for the different samples and their sizes. The analysis and obtained results prove that the developed MCLA sensor is a perfect candidate for adulteration detection. The same procedure could be extended to detecting the adulteration of any liquid samples. The method can be further extended to detect the adulteration of liquid samples with multiple adulterants, by detecting the possibility of identifying the individual adulterants. It can be made possible depending on the sensitivity of the sensor on individual adulterants.

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