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Microwave Sensors for Arsenic Detection Using Folded Complementary Circular Ring Resonator

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Abstract – **A microwave sensor working at around 2.4 GHz Wi-Fi frequency is proposed for rapid detection of arsenite/arsenate ions in water. The sensor consists of a planar folded complementary circular ring resonator (FCRR) etched on the top of the single sided copper clad substrate material, with a semi-cylindrical groove in the centre of the FCRR. The liquid material under test (MUT), filled within a cylindrical tube is placed in the groove. The key concept is the interaction of the EM wave with the material of different conductivity (*As* concentration) which results in change in reflection coefficient at a particular frequency. The dielectric constant varies negligibly for different concentrations of arsenic in the water hence, the change in the value of the reflection coefficient at a particular frequency is used to determine the arsenic content in the water sample. A reference set is generated by recording the variation of reflection coefficient indicating different arsenic concentrations. The sensor dimension is 40 mm X 40 mm and, the MUT is filled in a cylindrical tube with volume of approximately 4.83mm^3 which is placed within the groove. The sensor possesses a sensitivity of 3.9 ~ 4dB/0.05 ppm change in concentration.**

Keywords – **Microwave Sensors, Folded Complementary Ring Resonators, Arsenic Detection, Grooved Complementary Sensor Structure.**

I. INTRODUCTION

Microwave sensors [1] in planar technology offer numerous advantages that make them suitable for a wide range of applications. These sensors can be used for water quality measurement, particularly in applications where traditional methods might be cumbersome or impractical. They are preferred over other type of sensors because they exhibit several advantages such as non-contact mode of operation, its ability to penetrate through the non-conducting materials even in diverse environment such as dust, smoke, fog, etc., cost-effectiveness, versatility, appropriateness for real time operation, and its suitability for several applications [2]. Moreover, planar microwave sensors are small, have low profile, and can be implemented on a wide variety of different substrates and exhibit low cost, small size, and low profile. The operation of microwave sensor basically depends on the nature of interaction of microwave signal with the MUT since microwaves are very sensitive to the properties of the materials they interact with. Hence, these sensors can be used for material characterization and analysis based on the permittivity measurements. It is well known that because of the specific material attributes each material exhibits different reflection, absorption, and transmission characteristics when microwave signal impinges on it as, the dispersive properties of materials highly depend on their molecular level interactions and charge distributions at microwave frequencies. Consumption of arsenic (***As***) contaminated ground water is a serious health hazard in several geographical regions both for humans and animals and essentially requires simple sensing solutions. Different countries have specified different maximum permissible limits of ***As*** in water. In most cases the water monitoring systems/stations are installed at fixed locations close to the water reservoirs to monitor the quality of the water. In the past, several conventional methods have been proposed by researchers that require transportation of the water sample to the centralized testing facility resulting in the risk of altering and damaging the original sample. It also involves complex sample preparation processes leading to an increase in their operational cost. The measurement procedure requires bulky and expensive laboratory-based facilities and highly trained personnel to operate. Therefore, there is a great need for compact, low-cost, simple, and rapid ***As*** detection apparatus. In [3], a microwave sensor array consisting of sensing elements operating over frequency band of 1 GHz to 10 GHz is proposed. A microwave sensor using an open-end coaxial probe is reported for the real-time assessment of water quality in [4]. Design and fabrication of a conductometric biosystem is discussed in [5] for the indirect detection of arsenic in aqueous samples. However, most of the previously reported works are based on frequency shifting principle of the resonator resulting due to change in the characteristics of the MUT. With the intention to use a simple mobile phone for characterizing the ***As*** in drinking water which may not permit the use of the frequency shifting principle, a method based on change in notch magnitude at a specific frequency is exploited. It is to be noted that the limited bandwidth of the mobile phone antenna at Wi-Fi frequency restricts the effective use of frequency shifting principle. The possibility of characterization of ***As*** contaminated water using the method based on change in magnitude of the peak/notch is explained in the following paragraph.

The dielectric property of any material has two components, the dielectric constant, and the loss tangent. The magnitude of the notch, peak, or the quality factor depends mainly on the loss factor of the MUT. Thus, it follows that the imaginary part of the permittivity, or the loss tangent, of the MUT can be obtained from the data for the notch depth or peak magnitude, or from the quality factor [6]. The deeper the notch is, the greater the quality factor and the sensitivity in retrieving loss tangent can be achieved. The main aim of this study is to generate a reference set for values of reflection coefficient in correspondence with the concentration of the *As*

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in water at a particular frequency, so that only one parameter i.e., reflection coefficient is sufficient to detect the *As* contaminated water.

II. DESIGN AND SIMULATION

A. Sensor Design

The proposed sensor consists of a folded complementary circular ring resonator (FCRR) as shown in Fig. 1 (a). Instead of a conventional split ring resonator (SRR) [7], complementary split ring resonator (CSRR) structure [8-10], or complementary ring resonator (CRR), an FCRR configuration is adopted. It is worth mentioning that in comparison to a conventional SRR., CSRR and CRR, the proposed FCRR reduces the overall size almost by half, leading to a significant size reduction. Additionally, the proposed configuration remarkably enhances the mutual coupling between two folded rings, leading to increased sensitivity of the sensor. The FCRR structure with outer radii of 16 mm /14 mm, inner radii of 12 mm /10 mm and arc radii of 3 mm /1 mm giving an annular width of 2 mm throughout, is etched on a single sided square copper clad FR4 substrate of dimensions 40 mm X 40 mm X 1.5 mm. The substrate has a dielectric constant of 4.4, loss tangent value of 0.030, thickness of 1.57 mm, and copper clad thickness of 0.035 mm. The physical parameters of the sensor are devised in accordance with the target frequency of around 2.4 GHz, selected due to its unique characteristics and widespread usage of ISM band. Moreover, this frequency provides a balanced trade-off between range and resolution suitable for many sensing applications. In the center of the outer complementary ring a horizontal semi-cylindrical groove of 0.5 mm depth is made within the substrate in which the polyimide or polyester cylinder of 1.8 ~ 1.9 mm length and 0.8 ~ 0.9 mm radius containing the liquid MUT sample is placed as shown in Fig. 1(a) and (b). The fabricated prototype of the proposed sensor is shown in Fig. 1(c).

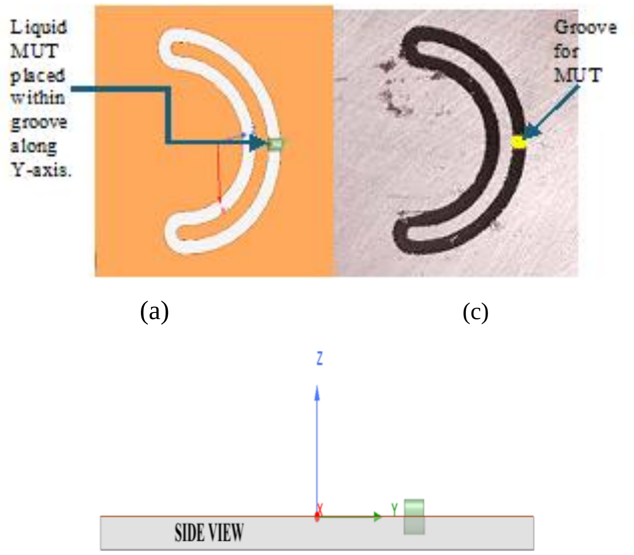

Fig. 1. Configuration of the proposed sensor: (a) Top View, (b) Side view, (c) Fabricated Prototype

The location of the groove for placing the MUT is decided based on the field concentration. The sample of the MUT kept within a cylindrical tube is placed along X- axis instead of Y-axis since this orientation would perturb the highly concentrated electric field to a greater extent as evident from Fig. 2. This perturbation of the electric field leads to a shift in the notch depth of reflection coefficient which varies for different As concentration.

The above design is simulated using Ansys HFSS simulation software, keeping the resonant frequency at around 2.4 GHz, exciting the structure using incident wave port and assigning lattice pair boundaries. Initially two major parametric analysis is carried out i.e., the variations of frequency and reflection coefficients with respect to size of the sensor and substrate thickness. First, an optimetric setup is designed with sensor size variation from 10 - 50 mm with a step size of 10 mm. The optimum sensor size for which the resonance lies within the 2.4 GHz range is found to be 40 mm as shown in Fig. 3. Next, an optimetric setup is designed with substrate thickness variation from 1-2 mm with a step size of 0.5mm. The optimum substrate thickness is obtained as 1.5 mm as shown in Fig. 4.

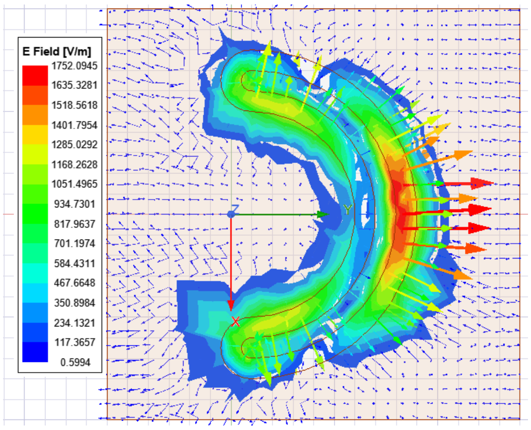

Fig. 2. Electric field concentration

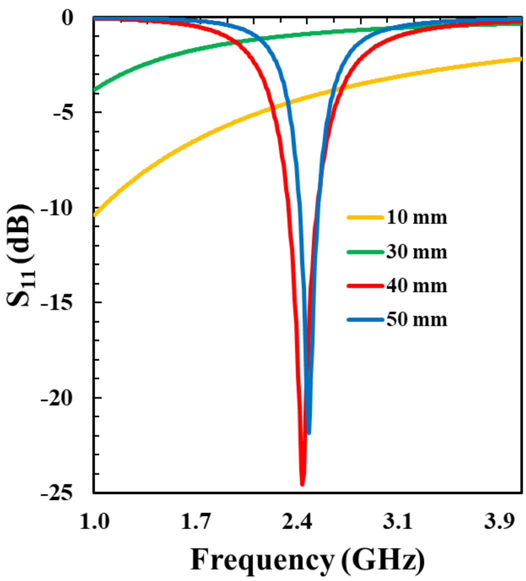

Fig. 3. Parametric Analysis for optimum sensor size

B. Simulation of Material under Test

Using equations 1 and 2, 0.33 mg of Arsenic Trioxide is dissolved in 5 ml of Sodium Hydroxide and then diluted with 250 ml of distilled water to prepare 1 mg/L of arsenic solution, which is diluted to 0.01 mg/L to avoid health risks [11-12].

$$As_2O_3 + NaOH \rightarrow NaAsO_2 \quad (1)$$
(As. Trioxide) (Sod. Hydroxide) (Sod. Arsenite)

$$NaAsO_2 + 2H_2O \rightarrow NaH_2AsO_4 + 2H^+ + 4e^- \quad (2)$$
(Sod. Arsenite) (Water) (Sod. Arsenate)

The dielectric parameters, that is, real and imaginary parts of relative permittivity and loss tangent are measured using dielectric probe kit (Agilent 85070E Dielectric Probe Kit 200 MHz to 50 GHz) and Vector Network Analyzer (VNA) over the desired frequency range. These dielectric parameters of the prepared samples are then fed into the simulation software to obtain the variation of notch depth of reflection coefficient with frequency.

The simulation is performed for various liquid samples, by assigning different material properties to the liquid MUT within the cylindrical tube placed within the groove. After verifying the optimum cell size and substrate thickness of structure for the target resonant frequency, the simulation is further carried out for various samples (normal water, distilled water, 0.01 ppm, 0.05 ppm and 0.1 ppm of Arsenic Solution). The structure resonates at around 2.4 GHz with significant S_{11} notch depths variations [7], [13-14] for various samples of liquid MUT inserted as depicted in Fig. 5.

One important feature of the proposed sensor is that varied concentration of ***As*** affects only the depth of the notch, while the resonance frequency is more or less unaffected. It is to be noted that zero variation in the notch frequency is important since it enables the proposed sensor to operate at a fixed frequency and facilitates the excitation of the sensor using a narrow band device.

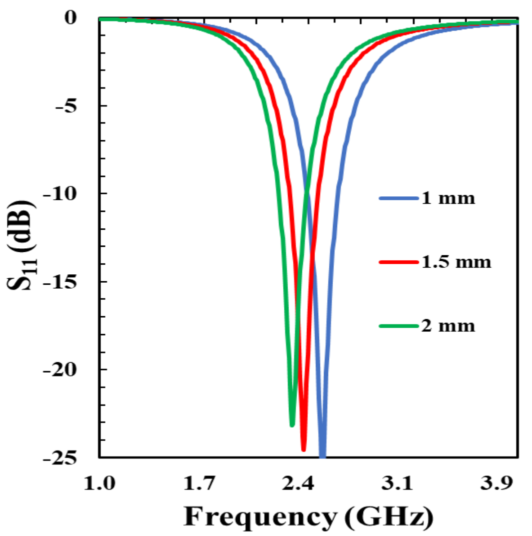

Fig. 4. Parametric analysis for optimum substrate thickness

III. FABRICATION AND TESTING

With inference drawn from parametric study and simulation, the structure is fabricated using wet etching and shown in Fig. 1(b). A groove depth of around 0.1~0.2 mm is made using the drill machine with appropriate drill bit. The liquid MUT is then injected into a cylindrical plastic tube made using pen refill which is of the same dimension (length = 1.8~1.9 mm, radius = 0.8~0.9 mm) as used in simulation. The proposed sensor structure is excited using waveguide excitation method by keeping it between two open ended S band waveguides. The ports P1 and P2 of both the waveguides are connected to VNA as shown in Fig 6. The samples are placed in the groove of the sensor depicted in Fig 1 and the reflection coefficient S_{11} is measured for various samples. The measured S_{11} as shown in Fig. 7 is compared with the simulation results and tabulated in Table 1. All the measurements are performed at the specified frequency for which the sensor structure is designed, and the reflection coefficient indicating the ***As*** content in the water is measured at that frequency only which remains constant for the specific liquid MUT.

Finally, the results obtained are compared with the results reported in [3], and [15-19] for other microwave sensors used for water quality and other liquid chemical characterization as shown in Table 2. As seen, the proposed sensor works at a single frequency based on the magnitude of the reflection coefficient by detecting a change in magnitude of S_{11} notch depth which changes due to the change in loss tangent of the material. It is to be noted that the resonant frequency is mostly a function of the real part of the permittivity (ε') and other circuit parameters (L, C, or physical dimensions of the resonator). The direct influence of loss tangent on the actual resonant frequency is negligible. The proposed sensor is based on a single contaminant narrowband response. Hence the application of the proposed sensor is only for those materials that show change in value of the loss tangent but depict little change in real part of the permittivity at a particular frequency. In comparison to other works in which SRR/CSRR/open loop resonator based wideband sensors are designed to detect other organic/inorganic compounds by observing frequency shift or S_{21} amplitude, the proposed work measures change in reflected power at a constant frequency with change in Arsenic concentration to create a reference table for indicating the harmful concentrations. Additionally, the proposed sensor requires a small quantity of the sample for measurements, the sensor is simple, compact, and portable.

The notch magnitudes observed in the reflection coefficients in both simulation and measurement results are plotted in Fig. 8. The magnitude of the notch is roughly linearly dependent with the concentration of the ***As*** solution. It is to be noted that sensors monitoring the frequency shift rather than notch depth variation are mostly designed for broadband sensing. However, the proposed sensor is based on sensing a parameter at a specific frequency, and detection of concentration of ***As*** in water is one such application of the proposed sensor.

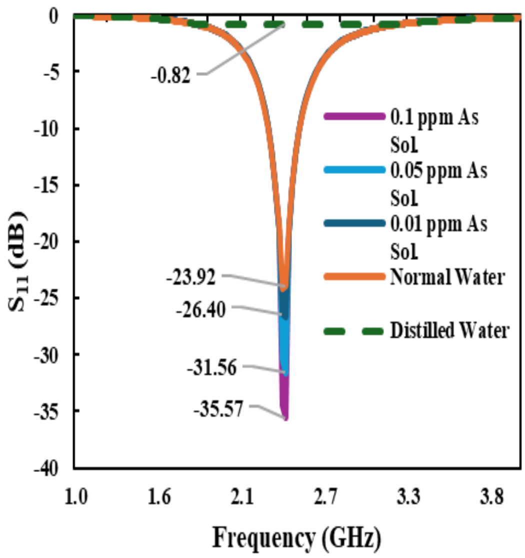

Fig. 5. Simulated Notch Depth Variation of reflection coefficient with different liquid samples.

TABLE 1
COMPARISON OF SIMULATION AND MEASURED REFLECTION COEFFICIENTS

MUT	Simulated S_{11} (dB) at f = 2.42 GHz	Measured S_{11} (dB) at f = 2.42 GHz
Distilled Water	**-0.81**	**-0.26**
Normal Water	**-23.920**	**-20.69**
0.01 ppm *As* sol.	**-26.395**	**-23.39**
0.05 ppm *As* sol.	**-31.561**	**-26.69**
0.1 ppm *As* sol.	**-35.567**	**-30.85**

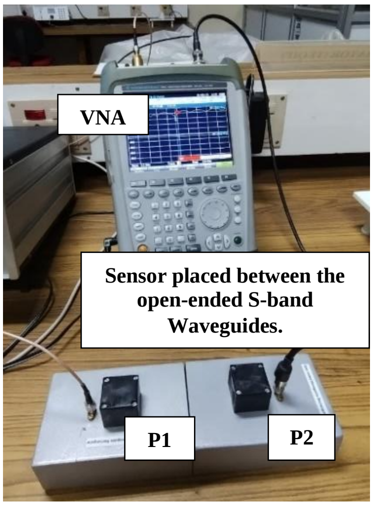

Fig. 6. Experimental Setup

IV. Conclusions

A novel microwave sensor is designed, fabricated, and tested for determination of the ***As*** content in the water. The proposed structure resonates at the target frequency of 2.4 GHz and yields consistent results when liquid MUT is placed in the groove. Additionally, the sensor is easy to fabricate, does not require any complex setup and provides a sensitivity of 3.9 ~ 4dB/0.05 ppm change in ***As*** concentration. The sensor would prove to be highly useful in generating a reference set of reflection coefficient values corresponding to specific amount of ***As*** content in the water sample using a very small amount of water sample. The layout is indeed a novel prototype, as in all the earlier reported work such simple grooved sensor structure has not been used for detection of arsenite/arsenate ions in water. The proposed sensor could be excited wirelessly as it resonates in UNII Wi-Fi band and could also help detect presence of unwanted metallic ions in potable or ground water. In future the measurement of the liquid MUT may be exploited using mobile phones with the help of suitable APP designed for detection of ***As*** content in water by extracting the power received by the phone which is dependent on reflection coefficient.

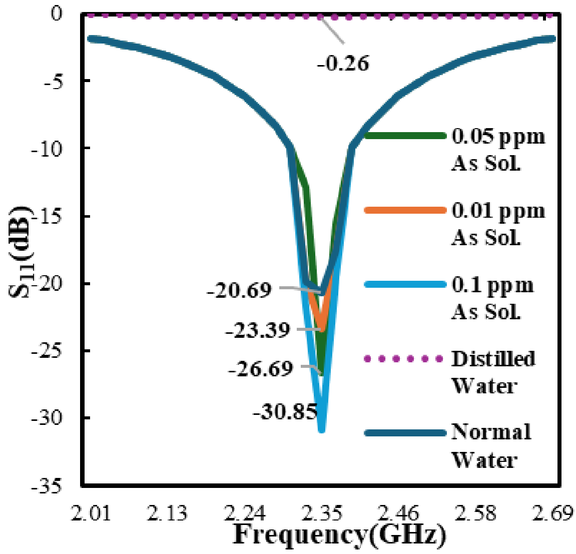

Fig. 7. Measured Notch Depth Variation of reflection coefficient with different liquid samples

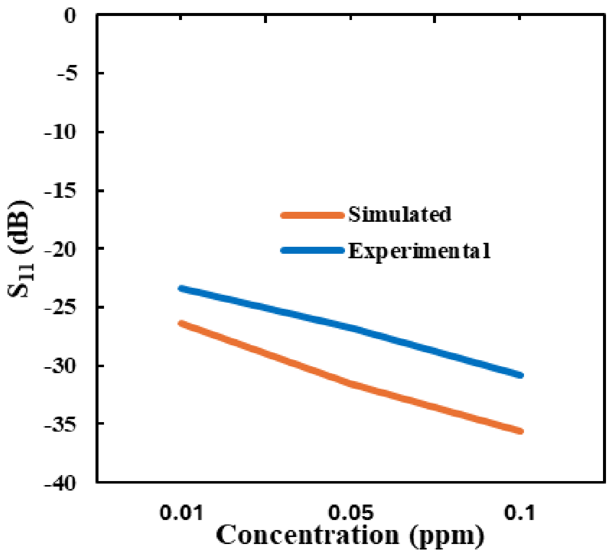

Fig. 8. Reflection coefficient variation with concentration

TABLE 2
COMPARISON OF PROPOSED SENSOR

Ref.	Sensor Structure	Freq. (GHz)	MUT	Sensing principle
[3]	CSRR Array	1-10	NO_3, PO_4, & NH_4 in water	Shift in Freq.
[15]	Inter-Digital Electrodes	1-15	CuCl, KCL, & $MnCl_2$ in water	Shift in Freq.
[16]	Double ring resonator	4.5-4.6	Organic contaminants in water	Change in amplitude of S_{21}
[17]	Metamaterial coupled open loop resonator	2.5	Concentrations of ethanol/methanol in water	Shift in Freq.
[18]	Two CSRR	2.45	Mixtures of methanol, ethanol, and water	Shift in Freq.
[19]	SRR	1.19	Methanol/Acetone in water	Shift in Freq.
Our work	FCRR	2.42	*As* in water	Change in magnitude of S_{11}

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