Electromagnetic Metamaterial Based Sensor Design for Chemical Discrimination

Debasis Mitra
Dept. of Electronics and Telecommunication Engineering,
Indian Institute of Engineering Science and Technology,
Shibpur, Howrah-711103, India
e-mail: debasisiit@gmail.com

Tarakeswar Shaw
Dept. of Electronics and Telecommunication Engineering,
Indian Institute of Engineering Science and Technology,
Shibpur, Howrah-711103, India
e-mail: tarakeswar.shaw@gmail.com

Abstract— **In this paper, a simple and efficient approach is presented for the design of a metamaterial based high sensitive chemical sensor. The sensor is designed by incorporating metamaterial Split Ring Resonator (SRR) unit cell within a small square loop. A high Quality-factor of 419 is obtained for the proposed design which is highly desirable in the field of sensing applications. Here, the proposed configuration is applied for chemical discrimination. The experimental results for various liquid samples, such as distilled water, alcohol and acetone are discussed. Also, the measurement of these three liquid mixtures is performed. The proposed metamaterial based sensor is small in size and compact in its shape.**

Keywords—metamaterial; split ring resonator; high-Q; chemical sensing.

I. INTRODUCTION

Nowadays, liquid chemicals are widely used in different industrial and clinical applications. Therefore, rapid detection and categorization of chemical samples have gained tremendous attention in clinical settings, drug discovery, security, safety and industrial applications.

Microwave sensors are usually preferred for many of biomedical, electronic and industrial applications [1]. These sensors provide different advantages such as robustness, high sensitivity, low fabrication costs and easy measurement procedure [2]. Due to these advantages, the microwave sensors become superior choices for biosensing and microfluidic applications. In [3], the microwave resonator method has been used for the measurement of complex permittivity of the biological liquids. To determine the complex permittivity of the samples, the transmission characteristics at resonance and the resonance frequency changes have been used. Also, the concentration measurement of liquid solutions with the help of microwave resonator has been presented and validated in [4]. However, for integrated system design, the sensors reported in [3] [4] are not suitable due to their large size. In [5], a compact microwave and microfluidic sensor has been demonstrated with complicated mathematical post-processing, dedicated to bioengineering application.

Recently, the design of metamaterial (MTM) based sensor has gained a tremendous attention in the field of microwave sensor design [6]. The metamaterials are artificially engineered metallic structures designed to obtain unusual material properties not available in nature. The resonance frequency of the MTM structures greatly depends upon the inductive and capacitive property of the resonator structure [7]. This property suggests that the MTM based structures are suitable for sensing applications. Also, these structures provide improved compactness and a high Quality-factor which is highly sensitive to change in environment [8]. Different types of sensors have been presented in the literature based on metamaterial for various sensing applications, such as thin-film sensing [9], rotation [10] and strain sensing [11]. Most recently, the metamaterial based microfluidic sensors have also been reported in [12] [13]. A microstrip coupled complementary split-ring resonator has been used for microfluidic dielectric characterization [12]. Also in [13], a dual gap meta-atom split-ring resonator has been used to determine the dielectric properties of the liquid. The microfluidic channels have been designed to provide the fluid sample to the resonators producing a significant variation of the resonance frequency elaborated in [12] [13]. However, these configurations need a large volume of liquid sample for characterization.

This paper presents a simple, compact and highly sensitive chemical sensor design by using MTM unit cell. The sensor is designed by incorporating metamaterial SRR within a small square loop. Here, the loop is used for the excitation of SRR. The overall size of the metamaterial based sensor is $0.14\lambda_0 \times 0.14\lambda_0 \times 0.02\lambda_0$, where λ_0 is the free space wavelength. A high Q-factor of 419 is obtained for the proposed sensor. The proposed configuration is designed and measurements are performed. The experimental result shows a shift in resonance frequency and return loss during the measurement of distilled water, alcohol and acetone.

The rest of the paper is organized as follows. The next section describes the characterization of metamaterial unit cell. In Section III, the configuration of the proposed liquid sensor using metamaterial unit cell is presented. The measurement setup and measured results for different liquid samples are discussed in Section IV. Finally, the conclusion is furnished in Section V.

II. DESIGN AND CHARACTERIZATION OF METAMATERIAL UNIT CELL

The schematic configuration of the metamaterial SRR unit cell used for the design of chemical sensor is shown in Figure 1. Also, the simplified circuit model is shown on the right side of the figure. The circuit is denoted by an LC tank where the resonant frequency is given by, $f_r = 1/(2\pi\sqrt{L_s C_s})$. The copper pattern which introduces self-inductances is represented by L_s and due to the cut in SRR results in capacitances denoted by C_s. The dimensions of the configuration are given in Table 1.

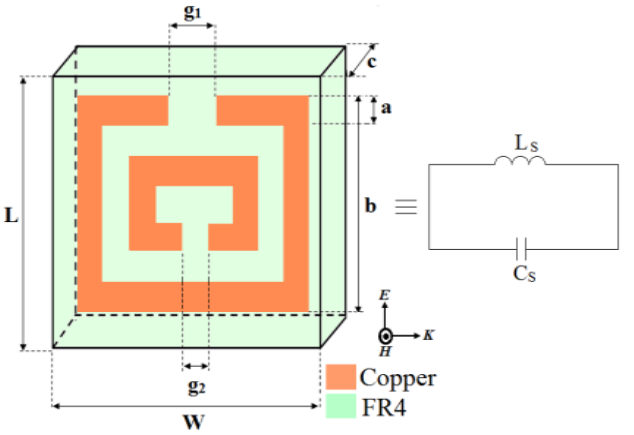

Figure 1. Configuration of metamaterial SRR unit cell and its simplified equivalent circuit model as an LC tank.

Here, the dimensions are optimized by the numerical simulation. The FR4 dielectric substrate is used to design the MTM unit cell has a dielectric constant of 4.4, the substrate thickness of 1.6 mm, and loss tangent of 0.02 with the copper pattern thickness of 0.017 mm. A parallel incident plane wave having a polarized electric field in the direction of x is considered for the calculation of the scattering parameters of the MTM structure. By using periodic boundary conditions, the reflection and transmission coefficients are obtained from a single metamaterial unit cell structure.

TABLE I. DIMENSIONS OF METAMATERIAL SRR UNIT CELL

L (mm)	W (mm)	b (mm)	g_1 (mm)	g_2 (mm)	c (mm)	a (mm)
6.7	6.7	5.8	2.4	1.2	1.6	0.6

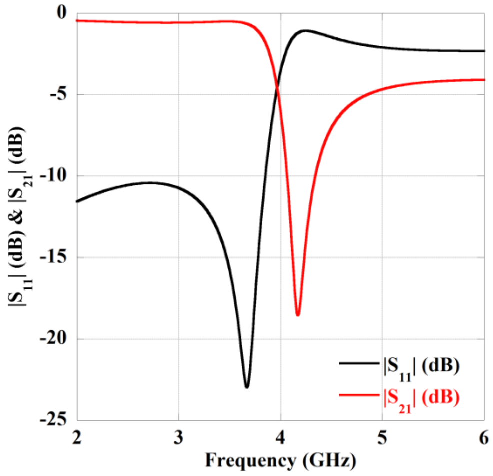

Figure 2. The simulated S_{11} and S_{21} characteristics of the SRR unit cell.

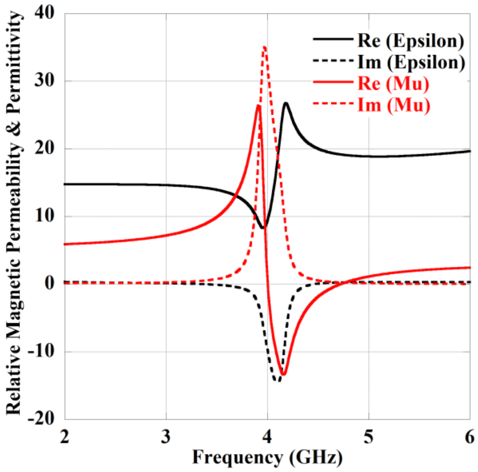

Figure 3. Retrieved relative magnetic permeability and relative permittivity of the SRR unit cell.

The simulated S-parameter plot of the unit cell is shown in Figure 2. The extracted relative magnetic permeability and relative permittivity characteristics of the SRR unit cell are also shown in Figure 3. The magnetic behavior is obtained from the SRR structure observed from Figure 3. The retrieval method has been used for the parameter extraction is described in [14]. All the simulations have been performed using the high-frequency structure simulator (HFSS-15).

III. SENSOR DESIGN USING METAMATERIAL UNIT CELL

In this section, the design of a compact metamaterial based chemical sensor is presented. The schematic configuration of the proposed metamaterial based sensor is shown in Figure 4. Here, the SRR unit cell discussed in the previous section is incorporated within a small square loop. The combined structure acts as a sensor. The different dimensions of the proposed configuration are given in Figure 4.

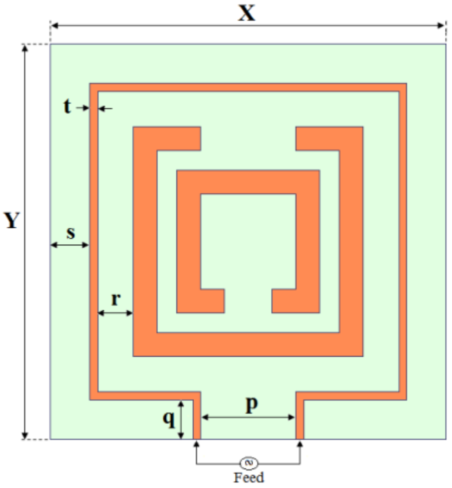

Figure 4. Schematic configuration of MTM based sensor and dimensions are in mm: X=10, Y=10, p=2.4, q=1, r=0.9, s=1, t=0.2.

A simulation has been performed using 50Ω characteristics impedance line coupled to the square loop as shown in Figure 4. The gap (r) between SRR and loop is optimized by numerical simulation to obtain a better matching in resonance frequency. As a consequence, a high Q-factor is obtained which is essential for sensing applications.

IV. RESULTS AND DISCUSSION

To verify the design concept, a prototype of the proposed sensor was fabricated and measurements have been performed for different chemical samples. The simulated electric field distribution of the proposed sensor at the resonant frequency is shown in Figure 5. From the figure, it is observed that the field density near the cut gap of SRR is much higher compared to other metallic parts. Hence, the disturbance of electric field by the liquid sample is highly sensed by these particular part. For this reason, during measurement of chemical response, only the SRR part is inserted into the sample to obtain the change in resonance frequency.

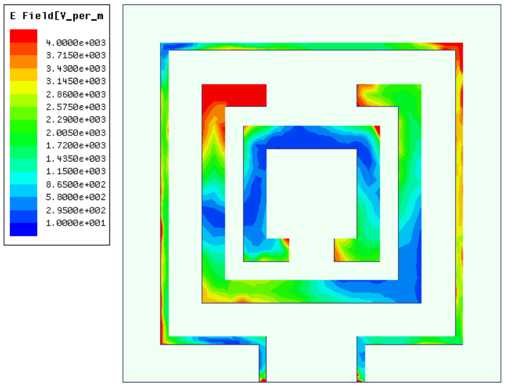

Figure 5. Simulated electric field distributions for the proposed sensor configuration.

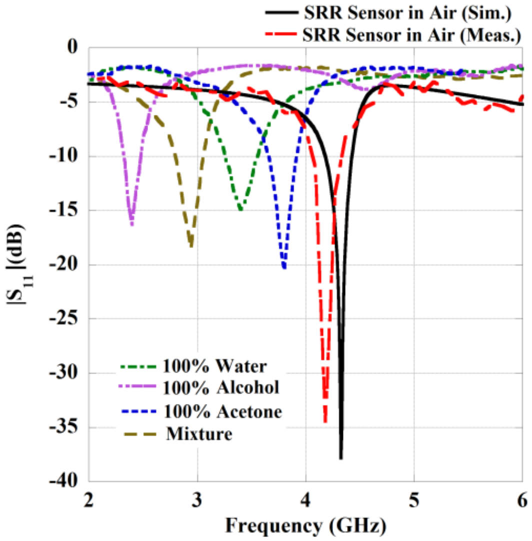

Figure 6. Simulated and measured return loss characteristics of the proposed sensor and different liquids.

The simulated and measured return loss characteristics of the SRR based sensor are shown in Figure 6. It can be pointed out from the figure that the measured resonant frequency of the sensor in the air is 4.19 GHz, whereas the simulated frequency is 4.32 GHz. The high Q-factor is obtained for the proposed sensor which is 432 for the simulated result, and 419 for measured result. The Q factor is defined as $f_r / \Delta f$, where f_r is the resonance frequency and Δf is the bandwidth at +3 dB with respect to the minimal reflection. The discrepancy occurred in between the measured and simulated results are due to measurement and fabrication tolerances.

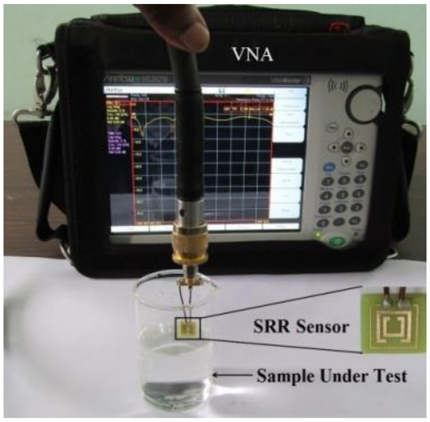

Figure 7. Measurement setup for the liquid sensor using vector network analyzer (VNA), in inset the fabricated prototype is shown.

The measured response of different liquids such as distilled water, alcohol and acetone is also shown in Figure 6. It can be observed from the figure that during the measurement of different liquid samples a huge shift in resonance frequency is observed. In case of 100% water, alcohol and acetone, the resonance frequencies are obtained at 3.4 GHz, 2.4 GHz, and 3.84 GHz, respectively with the return loss of -14.9 dB, -16.3 dB and -20.2 dB. Also, a measurement is performed with the mixture of water, alcohol, and acetone. It can be seen from Figure 6 that the resonance frequency of the liquid mixture is 2.94 GHz with the return loss of -18.64 dB. The measurement setup is shown in Figure 7.

V. CONCLUSION

In this paper, a metamaterial based high sensitive chemical sensor is proposed and designed. The sensor is designed by incorporating magnetic metamaterial SRR within a small square loop. The overall size of the metamaterial based sensor is $0.14\lambda_0 \times 0.14\lambda_0 \times 0.02\lambda_0$. A high Quality-factor of 419 is obtained for the proposed sensor configuration. The experimental results for the shifts in resonance frequency and return loss of distilled water, alcohol and acetone are studied. The sensor proposed here is simple in design and easily fabricated on the commercially available FR4 dielectric substrate by using metal etching procedure. The proposed metamaterial based sensor is small in size and compact in its shape.

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