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Metamaterial Based Sensor Using Fractal Hilbert Structure for Liquid Characterization

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***ABSTRACT*: In this work, a simple and efficient approach is presented to design a metamaterial based sensitive sensor for liquid characterization. The proposed sensor based on the Hilbert structure has a compacted size of 40×60×1.6 mm^3. The Hilbert curve is used to enhance the sensitivity of the sensor by increasing the interaction area with the sample tested. The simulation studies are carried out by using the Computer Simulation Technology (CST) Microwave Studio. The resonant frequency of the proposed sensor is about 0.46 GHz. The resonant frequency has shifted approximately 30 MHz after the receptacle is printed on the sensor surface. The proposed sensor has successfully detected different samples of liquids. The variations of the resonant frequency, scattering parameters, bandwidth and quality factor of different samples are discussed.**

***KEYWORDS*: Metamaterial, Hilbert, fractal, receptacle, liquid characterization.**

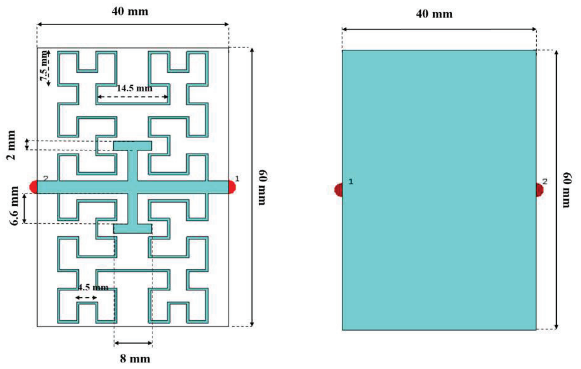
I. INTRODUCTION

A sensor is an electronic device that receives a signal or stimulation and responses with an electrical signal. Some types of electrical signals, such as current or voltage, are represented by the output signals. If the measured amount differs significantly, the electrical output changes constantly, as well, and the variations may be identified using their measurement capabilities [1-3]. Chemical sensor and biosensors have been created for medical and environmental purposes, explosive detection and a wide range of industrial uses. The essential attributes of fluidic sensors have been described, starting with the basic idea of metamaterial construction [3]. Metamaterials are intentionally designed periodic structures with negative permittivity and permeability at the same time [4,5]. They have been modified for different microwave and millimeter wave applications through design optimization. Their behavior is determined by their form, geometry, orientation and an appropriately stimulated electric/magnetic field. For example, the metamaterials used can define whether the sensor is sensitive to electric or magnetic fields, or both, as well as the operational frequency at which the resonance should occur [5]. Various forms of SRR, CSRR, and fractal structures, such as circular, square, triangular, and others [6-8], have been researched and used based on application needs. At microwave and millimeter wave frequencies, resonant components such as SRR, CSRR and fractal structures give a high-quality factor. The device dimensions, such as the inner radius, width of the ring/slot, split gap, and coupling gap between successive rings may be adjusted to tailor the components resonance frequency. Simulation techniques aid the identification of the structure's most vulnerable section [9].

For the characterization of liquids, this work presents a Hilbert fractal geometry based on metamaterial. The sensor is made up of a 50 Ω transmission line with T-resonators and a Hilbert-shaped fractal. The suggested sensor has been proved to be quite effective in detecting various liquids. The fractal shape is intended to provide a resonant frequency of 0.46 GHz, which is termed as f_0. Besides, fractal geometry is used to improve the selectivity by creating a broad region for electric field fringing, which increases the effective interaction area with the liquids under test. The liquids are placed in a FR4 receptacle that is installed on the sensor surface and is directly exposed to the fractal geometry electric field fringing.

II. SENSOR DETAILS

As shown in Fig. 1, the proposed sensor consists of three layers. The first layer is made from low cost (Flame Resistant) FR4 material. This layer is called the substrate layer with the physical size of 60×40×1.6 mm^3. The resonator layer consists of 50 Ω transmission line with T- resonator from two sides of the transmission line. T-resonator is used to increase the quality factor by decreasing the bandwidth. From Fig. 1(a), it can be observed that the resonator layer is based on Hilbert fractal geometry which is directly connected to the transmission line. The width of the traces of the Hilbert curve is 0.5 mm and it has copper thickness of 0.035 mm. The fractal geometry is intended to reduce overall size, improve sensitivity, and give a greater region of fringing electric field, which increases the effective interaction area with the sample. A metallic layer is used as the ground plane as shown in Fig.1 (b).



(a) (b)

Fig. 1 Geometrical details of the proposed sensor: (a) front view and (b) back view.

III. NUMERICAL ANALYSIS

The performance of the proposed sensor is simulated by using CST MWS. The resonant frequency of the sensor is approximately 0.46 GHz. The proposed sensor is suggested to characterize the liquids. Electric field distributions at the resonance frequency for the excitation of the sensor from two ports are demonstrated in Fig. 2. The liquid is placed on the sensor surface inside a receptacle which is made from the same material of substrate FR4.

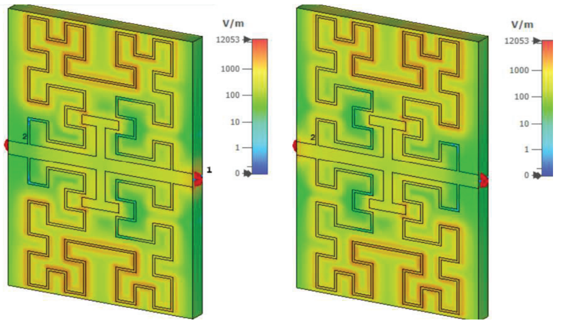


Fig. 2 Electric field distribution at the resonance frequency.

The shape of receptacle is chosen according to the electric field distribution that ensures the interaction between the liquid samples and electric field lines. Any variation in liquid sample can be investigated through monitoring the variation in the f_o and QF [10]. The receptacle has a rectangular geometry with size of 60×32×1mm^3 as shown in Fig. 3.

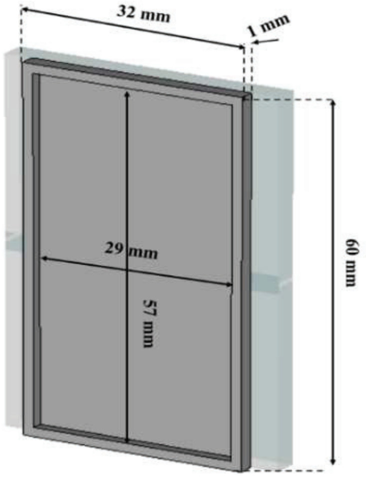


Fig. 3 Geometrical details of the proposed sensor receptacle.

The performance of the proposed sensor with and without receptacle is given in Fig. 4 in terms of S_{11} and S_{21}. The proposed sensor performance is calculated using CST MWS in terms of S_{11} and S_{21} spectra. For valuation, the authors conducted HFSS software package based on finite element method to obtain the S-parameters. As seen in Fig. 4, the obtained results from both software packages agreed very well.

Next, a numerical study is performed by introducing distilled water, sea water and oil which have different values of relative permittivity in the receptacle as the liquid under test. After loading the pan with the material under test, frequency resonance at the first mode is insignificantly affected as shown in Fig. 5. This ensured the choice of the first mode for detection. Thus, 0.468 GHz is determined as the frequency of operation for the detection process.

Finally, Table 1 summarizes the effects of introducing different liquids on the scattering parameters, resonant frequency, f_o, shift in the resonant frequency, Δf_o, bandwidth, BW, and quality factor Qf. The obtained data can be introduced to a classifier such as neural network that recognizes the material under test. An example of this process is applied in [11]. This is attempted by varying, numerically, the relative permittivity, epsilon (ε_r) of the martial under test inside the sensor receptacle from 1 to 100 with a step of 0.1. For such variation, the authors monitored the variation in f_o, Δf_o, S_{11}, S_{21}, BW, and Q_f for each ε_r step. The obtained results are introduced to neural network as training data. The results in Table 1 are validated by this algorithm. Neural network shows excellent agreement of detection based on the given training data. The maximum error variation of the neural network is given in Fig. 6. Mean squared error is found to be much less than the relative errors that were discussed in [12].

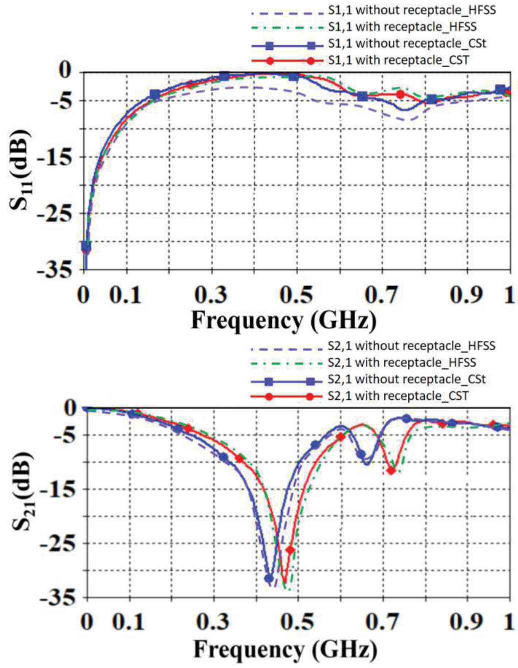
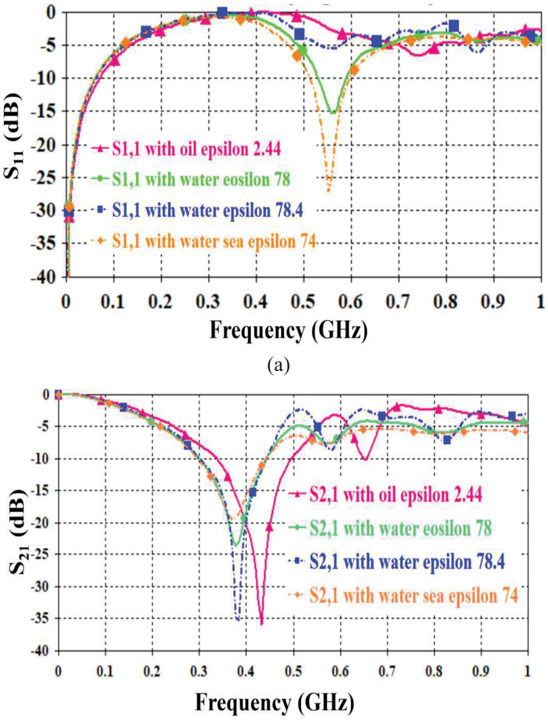


Fig. 4 S_{11} and S_{21} variations of the proposed sensor with and without receptacle.



(b)

Fig. 5 Variation of the S-parameters with different liquids under test: (a) S_{11}, and (b)S_{21}.

TABLE I. EFFECTS OF INTRODUCING DIFFERENT LIQUIDS ON THE SENSOR PARAMETERS.

Liquids samples	**f_o** GHz	**Δf_0** MHz	**S_{11}** dB	**S_{21}** dB	**BW** GHz	**Q_f**
Sensor without receptacle	0.468	0	-0.153	-32.56	0.0145	32.28
Sensor with empty receptacle	0.432	36	-0.147	-31.68	0.0169	25.56
Receptacle with Water (ε_r=78)	0.378	90	-0.77	-23.55	0.0272	13.90
Receptacle with Distilled Water (ε_r=78.4)	0.384	84	-0.303	-35.29	0.0094	40.85
Receptacle with Sea Water (ε_r= 74)	0.372	96	-1.151	-19.52	0.048	7.75
Receptacle with Oil (ε_r=2.44)	0.43	34	-0.164	-35.95	0.00723	59.57

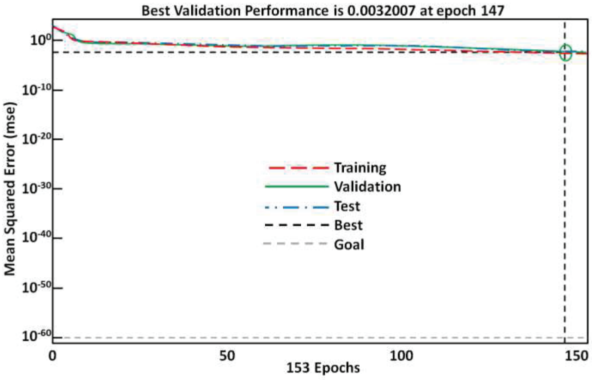


Fig. 6 Maximum error variations of the neural network.

IV. CONCLUSION

The proposed sensor is designed using metamaterial technology. It is constituted of a transmission line and a T-resonator that coupled to the Hilbert geometry. The liquid samples are deposited in a receptacle composed of the same substrate material. The suggested sensor operates at 0.46 GHz. The sensor detects introduction of different liquid samples successfully through the changes in the scattering parameters. The results showed insignificant shift in the resonant frequency for different liquids under test.

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