2024, 41st NATIONAL RADIO SCIENCE CONFERENCE
(NRSC 2024), April 16th– 18th, 2024,
Horus University in Egypt (HUE), New Damietta, Egypt

MULTIBAND COMPLEMENTARY SPLIT RING RESONATORS FOR NON-INVASIVE GLUCOSE MONITORING

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ABSTRACT

This paper presents a comparative study of transmission-based microwave sensor for rapid, precise, non-invasive blood glucose monitoring as an effective method for diabetes management and continuous monitoring. A comparative study between two shapes of Complementary Split Ring Resonator (CSRR) is conducted to realize a highly sensitive senor with low profile and high-quality factor. The proposed sensor design is made on a thin sheet of Rogers RT/Duroid 6002 dielectric substrate and includes three concentric CSRRs. To examine the sensitivity of the sensor, two sampling techniques for glucose solutions are used with concentrations from 0 mg/dL to 400 mg/dL. The established sensor exhibits a remarkable sensitivity of 0.067 degrees/(mg/dL) and 0.42 MHz/(mg/dL) to blood glucose levels and superior detection capabilities.

Keywords: *Non-Invasive, glucose monitoring, Complementary Split Ring Resonator.*

I. INTRODUCTION

Diabetes mellitus is a recurrent pancreatic syndrome that happens when your blood sugar (glucose) is too high or low than normal. Diabetes which affects people of all ages has different types. Diabetes is classified into four types: Type 1, Type 2, Gestational Diabetes, and Maturity-Onset Diabetes of Young (MODY). Type 1, also known as Juvenile diabetes, is a condition that typically results in an absolute lack of insulin due to pancreatic α-cell destruction. As a result, glucose homoeostasis cannot be sustained. Type 1 risk is mostly inherited, although there are other unclear environmental factors. Insulin resistance and, in some cases, a complete lack of insulin are two characteristics of type 2. Type 2 is significantly influenced by lifestyle choices. There was an 89% reduction in the incidence of type 2 among those who maintained a healthy weight, engaged in high levels of physical activity, avoided smoking, drank alcohol in moderation, and followed a nutritious diet. Gestational Diabetes is described as any level of glucose intolerance that arises or initially becomes apparent during pregnancy. It can happen at any stage of pregnancy but is more common in the second or third trimester. It happens when the pregnant woman body cannot produce enough insulin to meet the extra needs in pregnancy.

Recently, scientists have been motivated to perform more study in the field of continuous glucose sensing. There have been several blood glucose sensing technologies suggested till now, which may be classified as invasive, semi-invasive, or non-invasive. Direct arterial entry was used as the first invasive method of blood glucose measurement. This method is painful, and samples must be eliminated for testing by a qualified medical professional. The invasive measuring approach is more suited for patients who are restricted to area, such as in the intensive care unit (ICU), because the limitation causes discomfort for the patients. The advantage of an invasive approach is its high accuracy. This procedure takes time, however, because the blood must be collected 5-7 times each day for the blood glucose level test. Subcutaneous sensors and microdialysis are employed in minimally invasive measuring techniques to evaluate interstitial fluid and detect blood glucose levels. While the subcutaneous sensor requires needles for measurement, the latter does not. This is an advantage over past practice because, unlike the finger pricking method, subcutaneous sensors deliver measurements every 1-5 minutes for up to 7 days. Non-invasive testing does not require blood or interstitial fluid extraction, and neither does it require treatment that involves penetrating the skin. This procedure is therefore more suitable than those that were previously described in terms of patient comfort and suitability. The use of a non-invasive blood glucose test includes benefits including immunity to infection and painless monitoring on a regular basis. A medium like saliva, tear drops, or exhaled breath can be used for non-invasive monitoring. This is because of how simple it is to gather and access these fluids from the body. Principally, urine may also be used to measure glucose concentrations, but this method is not recommended for continuous blood glucose monitoring.

2024 41st National Radio Science Conference (NRSC) | 979-8-3503-4957-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/NRSC61581.2024.10510529

Microwave-based systems, as described in [1] and [2], require less power to operate and employ less expensive components, as well as the capacity to communicate with home devices such as mobile phones, laptop computers, WiFi, or smartwatches to monitor outcomes. Working at microwave frequencies will give safe sensing due to its non-ionizing nature and rapid detection time. This technology can generally be divided into three categories based on their characteristics: reflection, transmission, and resonant perturbation. In contrast, the resonant perturbation-based approach employs the Q-factor, whereas the transmission-based technique uses the transmission coefficients S_{21} and the reflection coefficients S11 [3]. The commonly used microwave circuits are Complementary Split Ring Resonators (CSRRs) due to its high sensitivity. In [4], CSRR is used to detect glucose changes in glucose solution from 25 to 300 mg/dL with sensitivity 1.20 MHz/(mg/dL). In [5], Triple pole CRSS is used to detect glucose changes in glucose solution from 70 to 120 mg/dL with sensitivity 0.0345 dB/(mg/dL). The proposed designs realized higher sensitivity compared to work in [4].

In this paper, the proposed CSRR sensors will be presented with low-profile, high-quality factor and better sensitivity. Also, the designs will sense the fine changes in glucose samples although the very similar dielectric properties in glucose concentrations. The designs can detect glucose samples ranging from 40 to 400 mg/dL, which represent varied glucose levels in the body. The proposed sensors are expected to operate in the 1-7 GHz range, with focus on 2.5 GHz and 5.8 GHz. A comparative study between two shapes of CSRR will be presented to get higher sensitivity for glucose measurements which is 0.067 degrees/(mg/dL) and 0.42 MHz/(mg/dL) to blood.

II. DESIGN DESCRIPTION

To obtain a miniaturized sensor, Complementary Split Ring Resonators (CSRR) are used with a band-stop filter behavior. However, CSRRs are etched in a metal layer. Instead of selecting a conventional shape, several shapes such as square and hexagonal CSRR resonators designs are included in the proposed study as shown in Fig. 1. The structure is created using the basic geometry of CSRR, as stated in [6]. To provide improved accuracy and sensitivity in the analysis, the sensor's resonant circuits should have a high Q-factor and have compact size. So, two CSRR design structures are studied in order to obtain a high sensitivity circuit. The resonant circuits of the sensors should have a high Q-factor and small size in order to ensure higher accuracy and sensitivity of the analysis. So, two design structures of CSRR are studied to get a high sensitivity circuit.

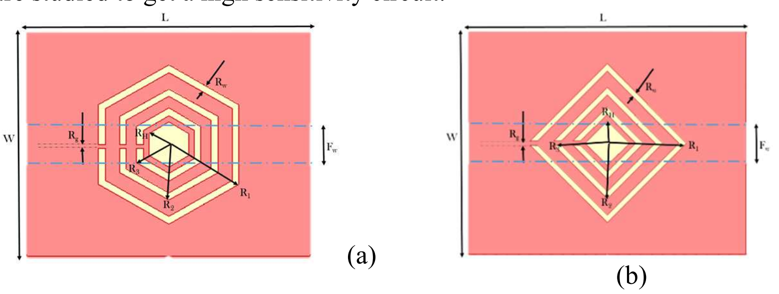


Fig. 1: Triple-rings sensor design: (a) ‘Hexagonal CSRR’ and (b) ‘Square CSRR’.

Using numerical simulations, the design on a conventional substrate was optimized to perform at a specific frequency band with a high degree of sensitivity at different glucose concentrations. According to optimization results, the proposed sensor as shown in Fig. 1 has substrate dimensions L = 25 mm and W = 20 mm. It is implemented on a substrate Rogers RT/Duroid 6002 (with dielectric constant $\varepsilon_r = 2.94$, loss tangent tan (δ) = 0.0012 and thickness h_{sub} = 3.048 mm). The proposed sensor consists of 3-concentric CSRR etched in the copper ground plane. The outer radii of the 3-rings are R_1, R_2 and R_3 and a cell in the middle of sensor whose radius R_H then the ring width and gap R_g. all dimensions of the proposed design are shown in table 1.

Table 1: Dimensions of the proposed sensor (all dimensions in mm).

Parameter	R_1	R_2	R_3	R_H	R_g	R_W	L	W	F_w	h_{copper}
Value (mm)	7.14	5	3.26	2	0.35	0.5	25	20	7.7676	0.07

This sensor is fed by a 50 Ω microstrip line with line width equals to 3.831 mm and soldered to a 50 Ω SMA coaxial connector to perform S-parameter measurements as shown in Fig. 1. All sensor dimensions are shown in Table 1. The operating frequencies of 2.5 GHz, 3.5 GHz and 5.8 GHz were chosen to match the Industrial, Scientific, and Medical band for ISM-band biomedical applications.

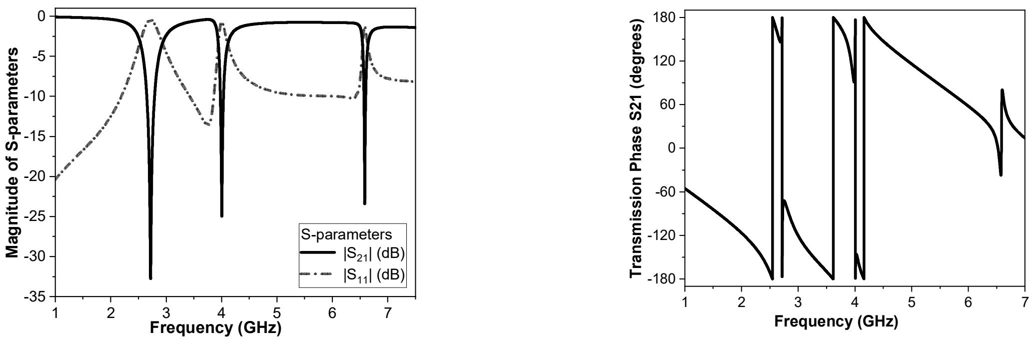
In this study, the CSRR’s structures was chosen due to its capacity to acquire high quality factor resonance peaks and sensitivity. These types of sensors are used for in-vitro measurements of aqueous glucose solutions. These design structures have many advantages over traditional Split Ring Resonators (SRR) as the electric field propagation strength increases in the sensing area. So, the sensor was developed with high Q-factor as shown in Table 2 in order to distinguish between glucose samples.

Table 2: Comparison between 2-shapes of Complementary Split Ring Resonators (CSRRs) in terms of resonance frequency and insertion loss.

CSRR	Hexagonal			Square		
	1st Resonance	***2nd Resonance***	***3rd Resonance***	***1st Resonance***	***2nd Resonance***	***3rd Resonance***
Frequency (GHz)	2.5415	3.758	6.0405	2.7195	4.0045	6.585
$\|S_{21}\|$ (dB)	-34.6023	-27.1864	-24.2622	-32.756	-24.9882	-23.3925
Q-Factor	65.6	117.1	168.5	55.6	101.8	228.2

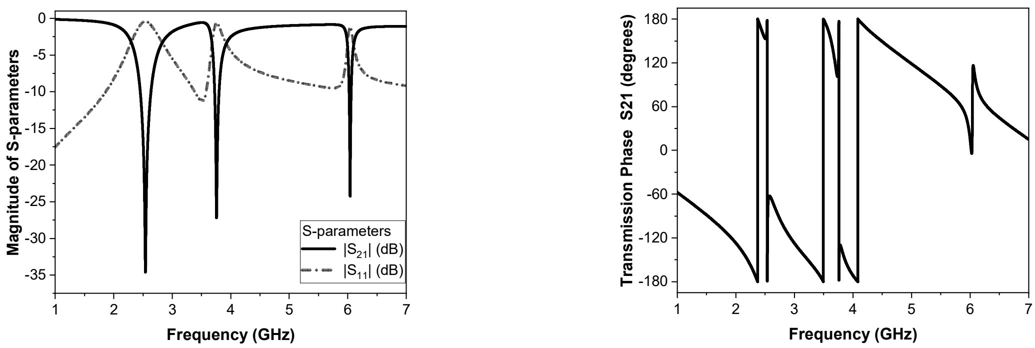
III. SIMULATION WORK ON AIR

To validate the proposed sensors, simulations were done using ANSYS HFSS simulation tool. ANSYS HFSS simulator is a three-dimensional full-wave electromagnetic field solution for high-frequency and rapid connectivity electronic component design. HFSS calculates the electrical behaviour of complicated components with any shape and user-defined material properties using a three-dimensional full-wave Finite Element Method (FEM) solver. Frequency analysis was done over a frequency range from 1 GHz to 7 GHz. S-parameters curves (S_{21} and S_{11}) are obtained to study the performance of the proposed sensors. Fig. 2 shows the S-parameters; S_{11} and S_{21} ,and S_{21} phase for the unloaded square CSRR circuit. Fig. 3 shows the S-parameters; S_{11} and S_{22} ,and S_{21} phase for the unloaded hexagonal CSRR circuit. Table 2 summarize the resonance peaks according to their magnitude of S_{21} parameter and resonant frequencies. Also, calculations for Q-factor were presented in Table 2.



(a) (b)

Fig. 2: S-parameters for unloaded square CSRR sensor: (a) S_{11} and S_{21} (b) S_{21} phase



(a) (b)

Fig. 3: S-parameters for unloaded Hexagonal CSRR sensor: (a) S_{11}, S_{21} and (b) S_{21} phase.

IV. GLUCOSE CHARACTERIZATION

The Cole-Cole relaxation model is frequently used to model the complicated permittivity of materials as shown in Eq. (1) [7].

$$\varepsilon^*(\omega) = \varepsilon' - j\varepsilon'' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau)^{(1-\alpha)}} + \frac{\sigma_s}{j\omega\varepsilon_o} \tag{1}$$

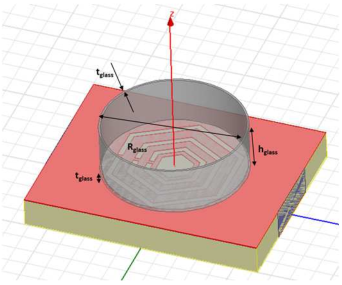
where ε^* , ε' and ε'' are the dielectric constant and dielectric loss factor values of a material, respectively, ε_s is the static permittivity, ε_∞ is the permittivity at infinite frequency, ω is the angular frequency, τ is the relaxation time, σ is the static conductance, ε_0 is the permittivity in free space, α is the exponent parameter. The equation simplifies to the Debye model when $\alpha = 0$. Furthermore, for low conductivity materials, the static conductance term can be eliminated. The published literature contains these criteria for any different materials, including biological matters [7]. This method may also be used for modelling aqueous glucose solutions. Table *3* shows the dielectric characteristics of these glucose solutions with different concentrations vary from 0 mg/dL to 400 mg/dL. It is clear that various glucose concentrations show small differences in values. Thus, it requires a highly sensitive sensor to be used to detect these small changes.

Table 3: Dielectric properties of glucose solution with respect to glucose concentrations vary from 0 mg/dL to 400 mg/dL at 2.5 GHz based on the Cole–Cole and Debye parameter polynomials

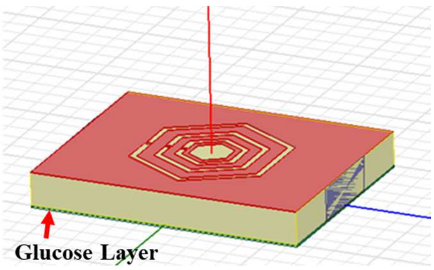
	Glucose Concentrations							
	0 mg/dL	***40 mg/dL***	***72 mg/dL***	***120 mg/dL***	***180 mg/dL***	***210 mg/dL***	***330 mg/dL***	***400 mg/dL***
$\boldsymbol{\varepsilon_r}$	78.622	78.606	78.605	78.618	78.656	78.682	78.775	78.883
σ_s **(S/m)**	2.4218	2.4236	2.4250	2.4269	2.4290	2.4299	2.4324	2.4344

V. Simulation work with glucose

In this section, solutions with different glucose concentrations are applied to the proposed sensors. Two scenarios for testing glucose samples with the proposed sensors are adopted as shown in Fig. 4. The first is to model the glucose solution as a thin layer on backside of the sensor of height 180 um. The second is built a glass container in the simulation and place on the front side (CSRR side as shown in Fig. 4 (a) with the glucose solution inside it. The glass container is modelled with dielectric constant of $\varepsilon_r = 5.5$, radius R_{glass} of 7.6 mm, height h_{glass} of 5 mm and thickness t_{glass} of 0.4 mm as shown in Fig. 4 (a).



(a)



(b)

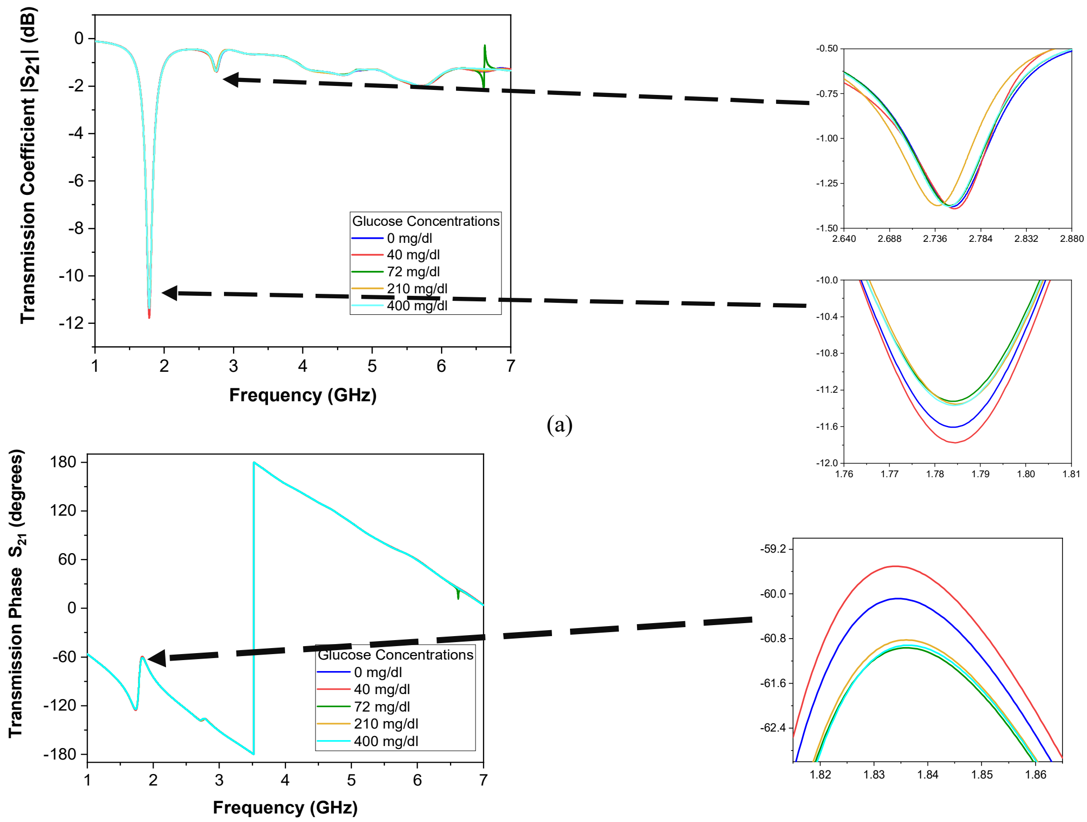
Fig. 4: (a) Triple concentric CSRR sensor with a glass container. (b) Triple concentric CSRR sensor with a thin glucose solution layer of 180 µm downwards the sensor.

A. Square CSRR Sensor

A glucose solution layer of 10 mm was added inside the glass container above the square CSRR circuit as shown in Fig. 4 (a). Optimization of the height of glucose sample in the glass container was conducted for better sample representation and sensing results. The glucose solutions concentrations vary from 0 mg/dL to 400 mg/dL. The reference of these measurements is that the concentration of glucose solution 0 mg/dL; which means there is no glucose in the solutions (distilled water). Then simulations are done to see its effect on the magnitude of S_{21} and phase curves. Fig. 5 shows S_{21} magnitude and phase curves for several glucose concentrations. It is clear that there is a shift in amplitude when adding a glucose solution layer with respect to 0 mg/dL curve. This shift happens due to change in dielectric material which is the glucose concentration. Table 4 shows the summery for amplitude and phase shifts; $\Delta|S_{21}|$, $\Delta\varphi$ respectively which happened with several glucose concentrations with respect to 0 mg/dL curves.

Another technique, that same glucose concentrations are modelled as a thin glucose solution layer of 180 um as shown in Fig. 4 (b) at the bottom layer. Fig. 6 shows S_{21} magnitude and phase curves for several glucose concentrations. It is clear that there is a shift in frequency when adding a glucose solution layer with respect to

0 mg/dL curve. Table 4 shows the summery for amplitude and phase shifts; $\Delta|S_{21}|$, $\Delta\varphi$ respectively which happened with several glucose concentrations with respect to 0 mg/dL curves. It's clear from the results that this sensor can't distinguish between 0 mg/dL, 40 mg/dL and 72 mg/dL. So, another design will be studied to get better sensitivity for glucose solutions at 2GHz.



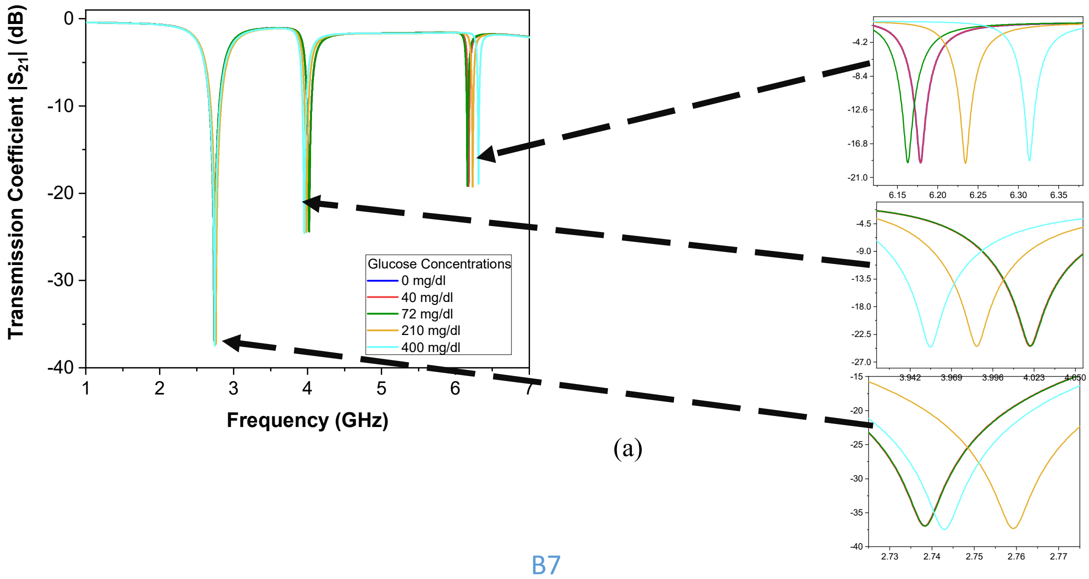
(a)

(b)

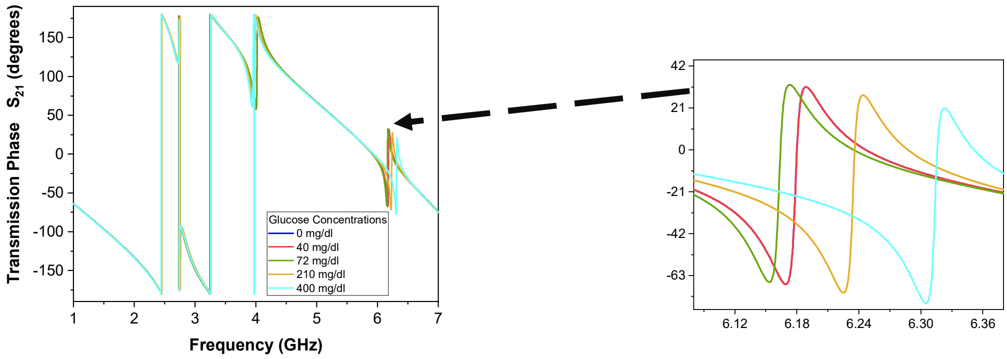
Fig. 5: Transmission response S_{21} as function of frequency for tested glucose samples of various concentrations inside a container above Square CSRR circuit. The transmission coefficient $|S_{21}|$ and phase (**a**) and (**b**) respectively.

Table 4: Simulation Results for amplitude and phase shifts for square CSRR sensor using a cylinder contains glucose solutions above the sensor at 2GHz.

	Glucose Concentrations			
	40 mg/dL	***72 mg/dL***	***210 mg/dL***	***400 mg/dL***
$\Delta|S_{21}|$ (dB)	-0.169	0.2832	0.2394	0.2528
$\Delta\varphi$ (degrees)	0.4966	-0.6832	-0.5558	-0.6103



(a)



(b)

Fig. 6: Transmission response S_{21} as function of frequency for tested glucose samples of various concentrations downwards on a square CSRR circuit. The transmission coefficient $|S_{21}|$ and phase (**a**) and (**b**) respectively.

Table 5: Simulation Results for frequency and phase shifts for square CSRR sensor using a thin layer of glucose solutions downwards the sensor.

	Glucose Concentrations			
	40 mg/dL	***72 mg/dL***	***210 mg/dL***	***400 mg/dL***
Δf (MHz) in 1st Resonance	0	0	21	4.5
Δf (MHz) in 2nd Resonance	0	0	35	84.5
Δf (MHz) in 3rd Resonance	0	16	55	165.45
Δφ (degrees)	0	0.9715	-4.266	-13.1108

B. Hexagonal CSRR Sensor

The same sampling techniques for putting glucose solutions are used as mentioned in the previous section. First, Sampling using the glass cylinder is applied. Fig. 7 shows S_{21} magnitude and phase curves for several glucose concentrations. It is clear that there is a shift in amplitude when adding a glucose solution layer with respect to 0 mg/dL curve.

Table ***6*** shows the summery for amplitude and phase shifts; $\Delta|S_{21}|$, $\Delta\varphi$ respectively which happened with several glucose concentrations with respect to 0 mg/dL curves. It's clear from the results that the response of this circuit is better than other square circuit. So, a small difference in glucose concentrations is applied to the other scenario to test this circuit sensitivity.

Table 6: Simulation Results for amplitude and phase shifts for hexagonal CSRR sensor using a cylinder contains glucose solutions above the sensor.

	Glucose Concentrations			
	40 mg/dL	***72 mg/dL***	***210 mg/dL***	***400 mg/dL***
Δ|S21| (dB)	0.0479	0.1606	0.2199	0.2349
Δφ (degrees)	-0.4229	-0.9559	-1.165	-1.5252

Then, a thin glucose solution layer of 180 um was applied as mentioned in the previous section. It is clear that there is a shift in frequency when adding a glucose solution layer with respect to 0 mg/dL curve. Table 7 shows the summery for amplitude and phase shifts; $\Delta|S_{21}|$, $\Delta\varphi$ respectively which happened with several glucose concentrations with respect to 0 mg/dL curves. Due to these results, as it is predicted this circuit has better sensitivity compared to the square CSRR circuit as there is a shift S_{21} curves. Also, this shift is consequence with all glucose concentrations.

As a summary of the performance of these two designs, it's found that the hexagonal CSRR circuit has a better sensitivity that square specially the band of 6 GHz (3rd resonance) with frequency shift almost equals to 0.42 MHz/(mg/dL) and phase shift in S_{21} equals to 0.067 degrees/(mg/dL). Also, the other frequency bands 2.5 GHz and 4 GHz (1st and 2nd resonance) has acceptable frequency shifts but not like the 3rd one. Over all hexagonal CSRR sensor is the best in terms of sensitivity.

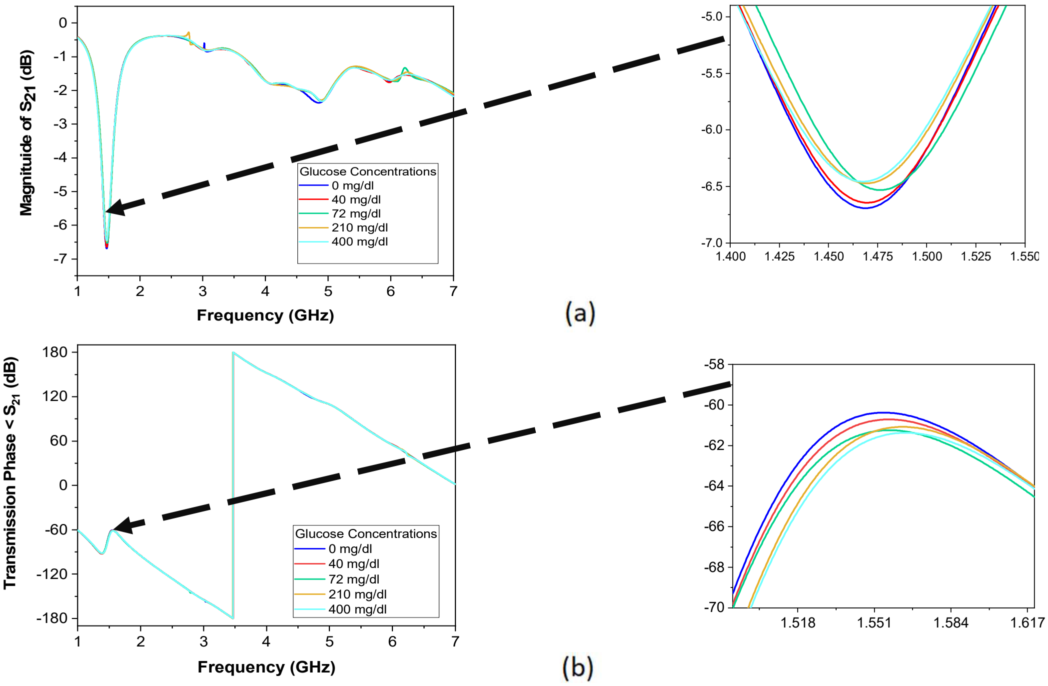


Fig. 7: Transmission response S21 as function of frequency for tested glucose samples of various concentrations on a container above hexagonal CSRR circuit. The transmission coefficient |S21 | and phase (**a**) and (**b**) respectively.

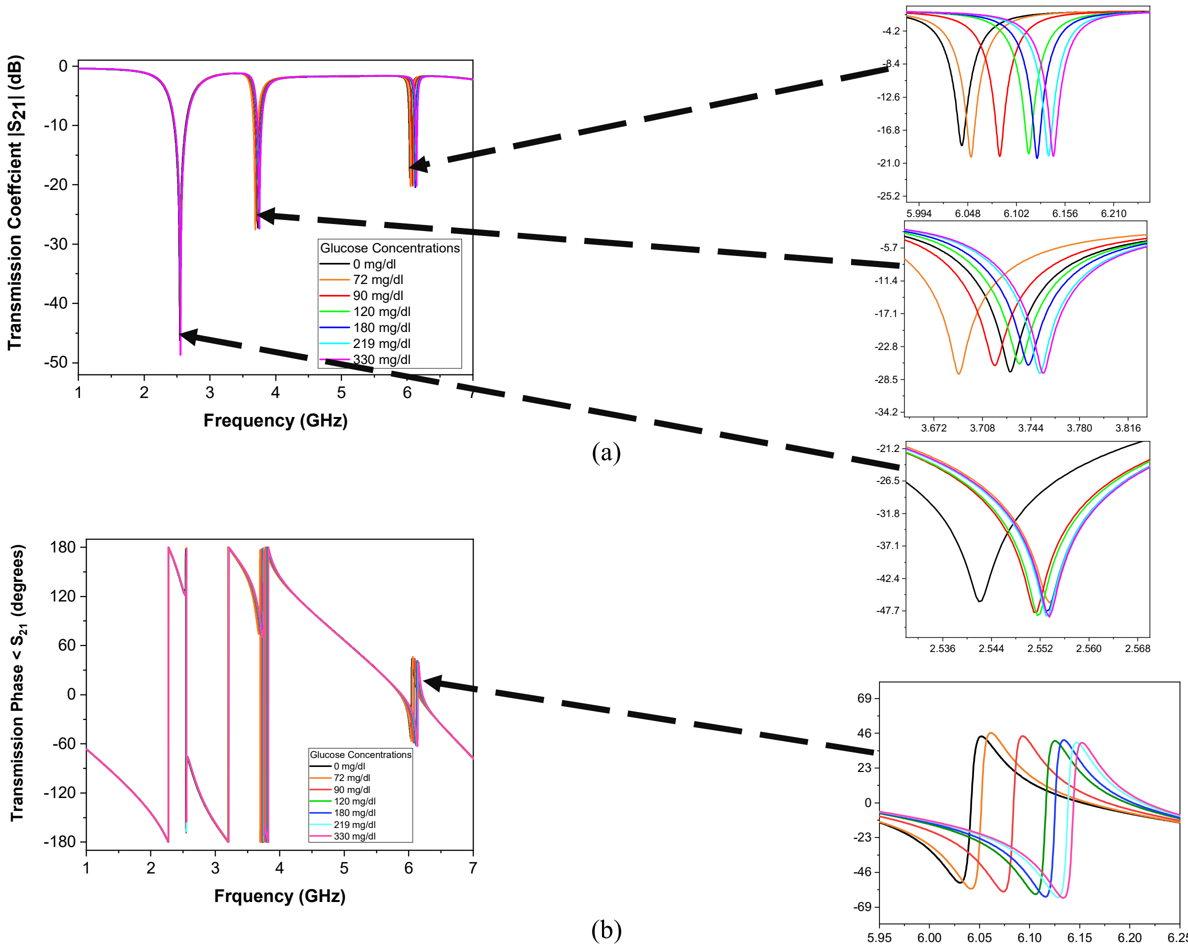


Fig. 8: Transmission response S21 as function of frequency for tested glucose samples of various concentrations downwards on a hexagonal CSRR circuit. The transmission coefficient |S21 | and phase (**a**) and (**b**) respectively.

Table 7: Simulation Results for frequency and phase shifts for hexagonal CSRR sensor using a thin layer of glucose solutions downwards the sensor.

	Glucose Concentrations					
	72 mg/dL	***120 mg/dL***	***180 mg/dL***	***210 mg/dL***	***219 mg/dL***	***330 mg/dL***
Δf (MHz) in 1st Resonance	11.5	9	9.5	11	11	11.5
Δf (MHz) in 2nd Resonance	-38.3	-11.8	6.7	13.2	17.2	24.2
Δf (MHz) in 3rd Resonance	10.2	42.2	74.2	83.7	92.2	101.7
Δφ (degrees)	3.7525	9.2334	11.8555	15.1024	16.8968	19.8161

VI. Conclusion

This paper presents a non-invasive microwave resonator based on Complementary Split Ring Resonator (CSRR) concept with its several geometries integrated with microfluidic system developed for the sensing of glucose solutions with different concentrations. Our work presents a simulation scheme for the microwave sensor with low profile and high Q-factor. As well as, it offers an effective solution for the non-invasive or potentially short distance transmission of electromagnetic waves and biomarker detection approach. The simulation results show its ability to sense small changes in glucose concentrations around the sensing area. The biosensing response was obtained based on the relationship between glucose concentration, insertion loss and resonant frequency. The measurement of various glucose aqueous solutions is based on changes in the dielectric properties of the sensor area, which result in considerable variations in insertion loss and resonant frequency. The simulation results show that hexagonal CSRR sensor has better sensitivity than square CSRR sensor. The proposed device can detect all glucose levels associated with diabetes, including hypoglycemia, normoglycemia, and hyperglycemia, with a sensitivity of 0.067 degrees/(mg/dL) and 0.42 MHz/(mg/dL). The proposed resonator has a better sensitivity than existing microwave sensors as an example, the sensitivity mentioned in [5] is 0.0345 dB/(mg/dL). Other advantages include its simple design, inexpensive price and little size, which allow it to be used as an initial test for blood glucose levels.

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