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Low-Cost CSRR Sensor for Determination of Glucose Concentration

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Abstract

Objectives: In this work, we have proposed a Complementary Split Ring Resonator (CSRR) based microwave planar sensor for the determination of glucose concentration in aqueous solutions. **Methods:** A triple-ring microwave planar resonator sensor has been designed using the HFSS software to detect glucose concentration in aqueous samples. The sensor is designed to operate at 2.4 GHz of the Industrial Scientific and Medical (ISM) band and is used to extract the transmission coefficient when samples under test are placed over it. The sensor is simple in design and proposed to be made out of low-cost FR4 material. **Findings:** The sensor is found to deliver high sensitivity (0.125 MHz/mg/dL) and is capable of distinguishing minor changes in glucose concentration through the detection of changes in the resonant frequency of the sensor with the permittivity of the test solution. Also, it is found that by developing a fit equation from the values of transmission coefficient (S_{21}), we can determine the dielectric constant of an unknown glucose sample, the accuracy of which is justified by its coefficient of determination, i.e., the R^2 value. **Novelty:** A novel triple-ring Complementary Split Ring Resonator (CSRR) with high sensitivity is proposed which requires a very small volume (around 38μL), which is an advantage over a commercial probe.

Keywords: Complementary Split Ring Resonator; Microwave sensor; Permittivity; Glucose concentration; Transmission coefficient

1 Introduction

In recent times, due to the change in our lifestyle, food habits, increasing anxiety and stress levels, and lack of physical labor, more and more people are being affected by diabetes- especially type 2 diabetes. The most accurate and low-cost method for monitoring blood glucose levels comprises using blood strips with finger pricking, which makes it an invasive, infectious, and painful testing method. Therefore, the need for a non-invasive technique for the same is always in high demand. In this respect, the microwave dielectric resonator method has been extensively used as a non-destructive and real-time monitoring technique. This method relies on the utilization of dielectric resonator units as the sensing element, which is preferred over other non-resonance methods due to their low cost, simplicity, and ease of miniaturization in modeling and manufacturing. The high sensing abilities, compact-form, and real-time monitoring capabilities of the metamaterial-inspired structure, such as Split Ring Resonator (SRR), and Complementary SRR (CSRR) incorporating planar microwave technology have been extensively used for many applications. Many groups have proposed SRR sensors to measure and monitor glucose concentration in aqueous solution[1,2]. However, for the identical dimensions, CSRR is found to perform better over SRR in terms of providing higher sensitivity and high-Quality factor[3]. A microwave sensor that comprises four triangular-shaped CSRR cells for the detection of glucose has been shown in[4]. The sensor has been fabricated on Rogers 6010LM and the sensitivity of the sensor is found to be 1.55×10^{-4} GHz/mg/dL. In our work, we have used an FR4 substrate to make the sensor low-cost. In[5], a narrow-band microwave sensor utilizing three CSRR cells has been presented for detecting glucose concentration in aqueous samples. A planar microwave resonator sensor incorporating four hexagonal-shaped CSRR units in a honey cell configuration for monitoring glucose concentration ranging from 40-140 mg/dL has been presented in[6]. The highest sensitivity of the mentioned work is 1.25 MHz/mg/dL. In all the above works, the design topology is complex. However, a simple open-ended transmission line loaded with a single rectangular CSRR ring has been presented in[7]. However, they have used high-cost RO4350 laminate substrate and the sensitivity is found to be 0.5×10^{-3} mg/dL. A microfluidic sensor implementing an inter-digital capacitor (IDC) in SRR topology with a microfluidic channel has been shown in[8]. The sensitivity of the work is found to be 2.60×10^{-2} MHz/mg/dL with glucose concentrations ranging from 0 to 5000 mg/dL.

The mentioned references suffer from the problems like limited sensitivities, complex design, the requirement of a large amount of sample, and the high cost of substrate used. With an objective to overcome these shortcomings and gaps, we have designed a simple and low-cost CSRR microwave sensor with high sensitivity to test different concentrations of aqueous glucose solutions. The proposed noninvasive glucose concentration analysis can be useful in designing a noninvasive blood glucose analysis system. The design and optimization of the sensor is carried out using the Ansys High-Frequency Structure Simulator Software (HFSS)[9] and is modeled to resonate in the licensed free ISM band, i.e., at 2.4 GHz. The main advantage of using this frequency of the microwave region is that many RF modules like Wi-Fi, Bluetooth, and some Radar systems work in this operating region and it enables the possibility of future integration of the sensor with them.

2 Methodology

The basic principle of the proposed sensor is the perturbation of the electric and magnetic field of the sensing element when it is made to interact with an external dielectric material. The inclusion of dielectric material in the vicinity of the sensor results in the overall modification of permittivity in the space between the transmission line and the resonator. This change in the equivalent capacitance of the sensor introduces a change in the resonant frequency of the sensor from its unloaded condition.

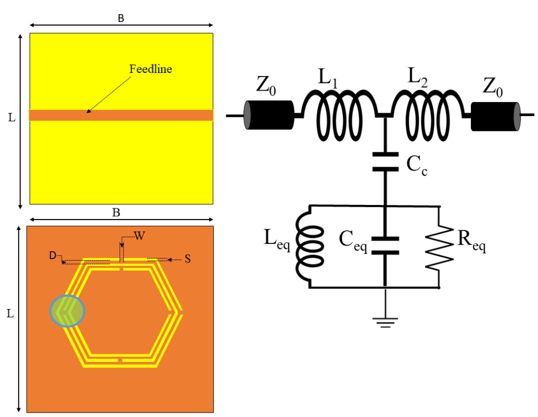

Fig 1. Design of the top and bottom plane of the sensor with the equivalent model

In this work, we have adopted a hexagonal-shaped triple-ring CSRR sensor having dual splits at right angles to each other in each of the rings to increase the capacitive effect. To excite the CSRR sensor, an axial electric field perpendicular to the plane of the CSRR is dispensed. For this, a microstrip line of width w = 0.8 mm is chosen to match with the standard 50Ω impedance.

Both SRR and CSRR can be modeled as parallel resonant tank circuits (parallel RLC circuits), with the metal portion and the gaps acting as inductance and capacitance in SRR. While in CSRR, the etched portion act as the capacitor and the metal split gap acts as the inductor. The impedance R is due to the dielectric losses in the system. Based on the concept of acting as a parallel LCR circuit, the lumped equivalent circuit model of the proposed sensor has been modeled in the KEYSIGHT

Advanced Design System software (ADS) [10]. The model describes the CSRR to be capacitively coupled to the transmission line by a capacitance C_c. The CSRR is a parallel shunt circuit with equivalent capacitance C_{eq} and inductance L_{eq}, respectively as shown in Figure 1.

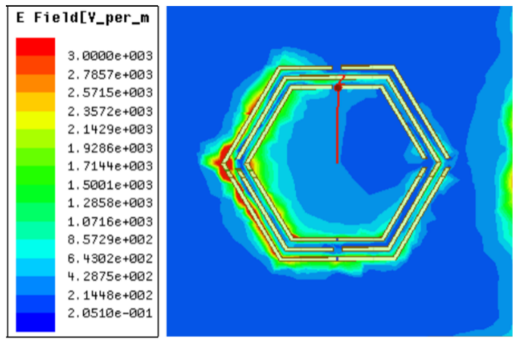

Fig 2. Electric field concentration of the resonator

3 Results and Discussion

The permittivity dependence of glucose on frequency is due to its complex nature, and this dependence is higher in the high-frequency region as the β and δ dispersion region of blood falls in the microwave spectrum. In these two regions, blood permittivity variation is largely dependent on frequency, and hence the detection of glucose concentration using microwave frequency is preferred. For this reason, a simulation of a non-invasive microwave sensor is carried out to detect glucose levels in aqueous solutions. The variation of frequency of transmission notch (Transmission coefficient S_{21}) is taken as the measure to evaluate the glucose concentration in water.

The dimension chosen for the substrate is LxB=(20x20)mm^2. The optimized Split gap is found to be 0.5mm, whereas the distance between the two rings as well as the width of the rings, is found as D=S=0.26mm. These optimized parameters are modeled to obtain an unloaded resonant frequency of around 2.4 GHz. The CSRR is etched on the bottom side of a low-cost FR4 dielectric substrate with ε_r=4.4 and tanδ=0.03

A glass holder, which is made out of a cylinder with an outer and inner radius of 4 mm and 3 mm, respectively, is placed to cover the maximum field intensity region of the resonator, which is shown in Figure 2. The effect of placing the glass holder (ε_r=5.5) has a minimal shift in resonant frequency towards the left, which is consistent with the theory. This holder is used to hold the solutions in contact with the resonating element. Now, in order to mimic the actual blood glucose levels in a human body, the same can be approximated by different proportions of water/glucose solutions. The aqueous glucose solutions mimicking the actual glucose in the blood are prepared by mixing glucose with 100ml DI water [11].

To obtain the complex permittivity values of the aforesaid glucose levels, by using Debye equations, the permittivity can be expressed as functions of angular frequency ω and the concentration χ of the solution.

$$\varepsilon_r(\omega,\chi) = \varepsilon_\infty(\chi) + \frac{\varepsilon_{stat}(\chi) - \varepsilon_\infty(\chi)}{1 + j\omega\tau(\chi)} \quad (1)$$

where, $\varepsilon_\infty\ (\chi)$ and $\varepsilon_{stat}\ (\chi)$ are the values of complex permittivity at high frequency and low frequency, respectively. $\tau(\chi)$ is the relaxation time of the solution considered. These three-concentration dependent parameters have been modeled for aqueous solutions.

$$\varepsilon_\infty(\chi) = 5.38 + 30 \times 10^{-3} \times \chi \quad (2)$$

$$\varepsilon_{stat}(\chi) = 80.68 - 0.207 \times 10^{-3} \times \chi \quad (3)$$

$$\tau(\chi) = 9.68 + 0.23 \times 10^{-3} \times \chi(ps) \tag{4}$$

The determination of complex permittivity and loss tangent is then carried out from the following equations.

$$\varepsilon_r = \varepsilon_r' - \varepsilon_r'' \tag{5}$$

$$tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{6}$$

As this study is based upon simulation, the permittivity values are taken from the already computed values of the glucose concentration samples as obtained in[11]. The concentration of the considered samples along with the Debye relaxation parameters is listed in Table 1, as published in[11].

Table 1. Debye Coefficients of glucose concentrations

Glucose samples mgdL^{-1}	$\varepsilon_\infty\ (\chi)$	$\varepsilon_{stat}\ (\chi)$	$\tau(\chi)$	$\varepsilon_\gamma{}'$	$\varepsilon_\gamma{}''$
67	7.39	80.6786	9.6954	73.2761	11.2266
280	13.78	80.6742	9.7444	66.842	9.5559
400	17.38	80.6717	9.772	63.2172	8.8304

First, the bare sensor is simulated to get its unloaded operating resonant peak frequency which is found to be 2.44 GHz. Then, the effect of the glass sample holder is taken into account by simulating the same with the sensor, and the change is shown in Figure 3. Additionally, a very thin layer of glass having a thickness of 0.1 mm is placed above the maximum sensing area of the resonator to avoid the loss effects due to glucose samples. Now to detect the concentration of glucose samples, the sample with 67mg/dL is used first to simulate the sensor in the HFSS software. The peak frequency and the magnitude of transmission coefficient (S_{21}) in dB are noted. Similarly, the other remaining samples with their respective complex permittivity values are used one after another in the simulation process. A small volume of around 38μL is filled in the holder, which is an advantage over a commercial probe in which the requirement of the volume of samples is more. The resonant frequency with the glass holder as well as the glass layer is taken as the reference level. The changes in the respective (S_{21}) notch are shown in Figure 4 with respect to the reference value. The higher the glucose concentration lower the permittivity of the DI-glucose solution. The range of the discrete-type frequency sweep starts with a frequency of 0.5 GHz and ends at 3 GHz.

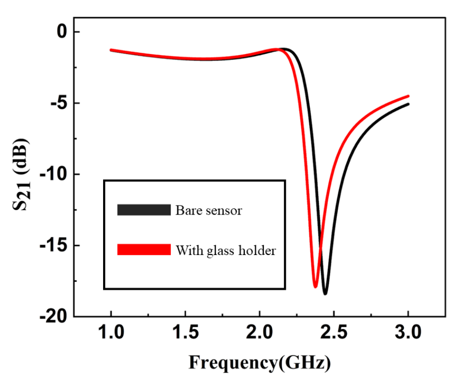

Fig 3. S_{21} coefficient in case of bare sensor and the sensor with the glass holder

3.1 Quality Factor (Q) and sensitivity performance of the sensor

The Quality factor (Q) describes the power absorbed in the resonator. The found unloaded Q factor of the proposed resonator is around 100, which is a moderate value considering the high losses of the substrate considered. Although, this factor can be significantly improved by the use of lower-loss tangent substrates.

In addition to the Q factor, the sensor can also be characterized in terms of its performance by its sensitivity which can be evaluated by the following equation [12].

$$S = \frac{\Delta f}{\Delta \varepsilon} \tag{7}$$

Where, Δf represents the change in resonant frequency, and $\Delta \varepsilon$ is the difference in permittivity value of the sample with respect to the reference. The sensitivity is found from the values obtained as shown in Figure 4. The calculated value of sensitivity in percentage is found to be S_{avg}=10.33794 and the sensitivity with concentration is found to be 0.125MHz/mg/dL.

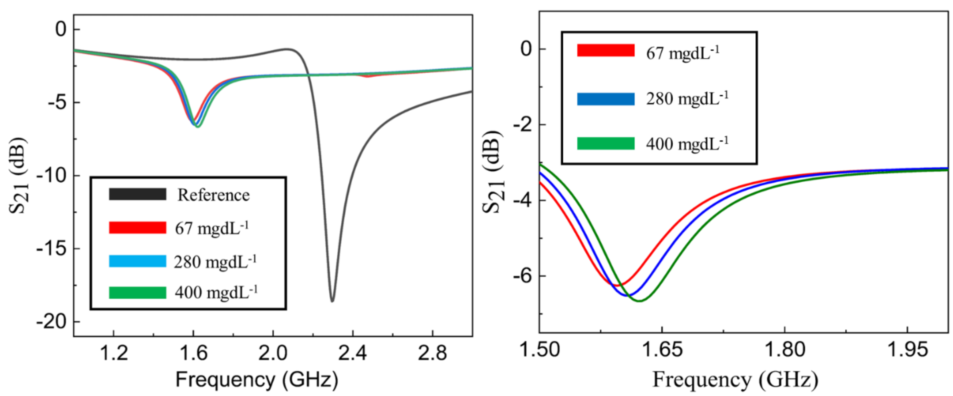

Fig 4. S_{21} magnitude and notch frequency

3.2 Fitting curve for detecting the concentration of aqueous glucose solution

For detecting the concentration of glucose in water/glucose solutions, a fitting curve is developed with the respective values of the peak frequency obtained from the simulation and the concentration values as obtained from [11]. The found-fitting graph is shown in Figure 5, and the equation of fitting is

$$mgdL^{-1} = -532000f^2 - \left(2\times 10^6\right) f - \left(1\times 10^6\right) \tag{8}$$

By knowing the value of the respective resonant frequency of an unknown aqueous glucose sample, it is possible to detect the concentration of the glucose sample from the above relation.

3.3 Comparison of the proposed sensors with recent works

To validate our findings with some previous works, a comparison has been carried out and the same has been presented in Table 2. It is seen that for most of the works, the volume of samples used is high in comparison to this work. Also, some of the mentioned references deal with a complex design for the analysis of glucose concentration. However, we have implemented a simple and low-cost design made on FR-4. The high sensitivity obtained with this sensor is possible due to the high concentration of electric field leading to enhanced interaction of the sample with the sensor. On the basis of the comparison, the superiority of our presented work can thus be established.

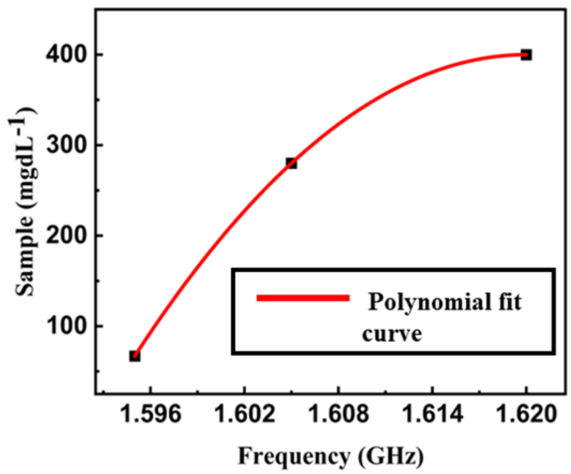

Fig 5. Polynomial fitcurve for detection of glucose

Table 2. Comparison table of the proposed sensor with other works

Ref.	Sensor Type	Sample μ l	Substrate used	Sensitivity MHz/mg/dL
(4)	Complex CSRR	400	Rogers 6010LM	1.55 X 10^{-1}
(6)	Complex CSRR	600	FR-4	1.25
(7)	Simple CSRR	NA	RO4350	0.5
(8)	Complex SRR	NA	RT6006	2.60 X 10^{-2}
This work	Simple CSRR	38	FR-4	0.125

4 Conclusion

In this work, a simulation study is carried out with three different aqueous solutions in different proportions of glucose levels. As the concentration of glucose is increased, the dielectric permittivity is observed to decrease. A highly optimized and sensitive novel three-ring hexagonal-shaped CSRR sensor with two slits normal to each other is proposed to detect these changes in the permittivity values as a function of frequency. The shifts in the respective resonant peaks for the three glucose/water solutions justify this change in permittivity values. For a very small volume of aqueous glucose around 38μL, the sensor with sensitivity 0.125 MHz/mg/dL is capable of distinguishing glucose concentration with good accuracy. Also, for this functional relationship between concentration and frequency, a polynomial curve fit is developed to obtain a relation of the glucose concentration as a function of the resonant frequency. The accuracy of the fit equations is justified by its coefficient of determination, i.e., the R^2 value.

The novelty of this work is the unique three-ring hexagonal-shaped double split CSRR sensor which requires an extremely small amount of sample for distinguishing different glucose concentrations. The proposed sensor has the prospect of being utilized as a non-invasive human blood glucose monitoring device. A sensor of this type can be used to eliminate the painful invasive human blood glucose testing.

5 Declaration

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References

1) Juan CG, Bronchalo E, Potelon B, Quendo C, Avila-Navarro E, Sabater-Navarro JM. Concentration Measurement of Microliter-Volume Water–Glucose Solutions Using Q Factor of Microwave Sensors. *IEEE Transactions on Instrumentation and Measurement*. 2019;68(7):2621–2634. Available from: https://doi.org/10.1109/TIM.2018.2866743.
2) Govind G, Akhtar MJ. Metamaterial-Inspired Microwave Microfluidic Sensor for Glucose Monitoring in Aqueous Solutions. *IEEE Sensors Journal*. 2019;19(24):11900–11907. Available from: https://ieeexplore.ieee.org/document/8822476.

3) Buragohain A, Mostako ATT, Das GS. Low-Cost CSRR Based Sensor for Determination of Dielectric Constant of Liquid Samples. *IEEE Sensors Journal*. 2021;21(24):27450–27457. Available from: https://doi.org/10.1109/JSEN.2021.3124329.
4) Sun Z, Zhang H, Zhang S, Zhang N, Li K, Wang X. A Microwave CSRR Sensor for Non-Invasive Glucose-Level Detection. In: 2022 IEEE 5th International Conference on Electronic Information and Communication Technology (ICEICT), 21-23 August 2022, Hefei, China. IEEE. 2022. Available from: https://ieeexplore.ieee.org/document/9909431.
5) Pecorella GR, Verderame G, Lombardo A, Livreri P. High-sensitivity narrow-band CSRR-based Microwave Sensor for Monitoring Glucose Level. In: 2022 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), 16-19 May 2022, Ottawa, ON, Canada. IEEE. 2022. Available from: https://ieeexplore.ieee.org/document/9806523.
6) Omer AE, Shaker G, Safavi-Naeini S, Kokabi H, Alquié G, Deshours F, et al. Low-cost portable microwave sensor for non-invasive monitoring of blood glucose level: novel design utilizing a four-cell CSRR hexagonal configuration. *Scientific Reports*. 2020;10(15200):1–20. Available from: https://doi.org/10.1038/s41598-020-72114-3.
7) Ebrahimi A, Scott J, Ghorbani K. Microwave reflective biosensor for glucose level detection in aqueous solutions. *Sensors and Actuators A: Physical*. 2020;301:111662–111662. Available from: https://doi.org/10.1016/j.sna.2019.111662.
8) Govind G, Akhtar MJ. Metamaterial-Inspired Microwave Microfluidic Sensor for Glucose Monitoring in Aqueous Solutions. *IEEE Sensors Journal*. 2019;19(24):11900–11907. Available from: https://doi.org/10.1109/JSEN.2019.2938853.
9) 3D High Frequency Simulation Software. . Available from: https://www.ansys.com/en-in/products/electronics/ansys-hfss.
10) PathWave Advanced Design System (ADS) Software. . Available from: https://www.keysight.com/us/en/lib/software-detail/computer-software/pathwave-advanced-design-system-ads-software-2212036.html.
11) Mohammadi P, Mohammadi A, Demir S, Kara A. Compact Size, and Highly Sensitive, Microwave Sensor for Non-Invasive Measurement of Blood Glucose Level. *IEEE Sensors Journal*. 2021;21(14):16033–16042. Available from: https://doi.org/10.1109/JSEN.2021.3075576.
12) Ebrahimi A, Scott J, Ghorbani K. Ultrahigh-Sensitivity Microwave Sensor for Microfluidic Complex Permittivity Measurement. *IEEE Transactions on Microwave Theory and Techniques*. 2019;67(10):4269–4277. Available from: https://doi.org/10.1109/TMTT.2019.2932737.