Progress In Electromagnetics Research Letters, Vol. 123, 83-88, 2025

PIER Letters

(Received 3 September 2024, Accepted 13 November 2024, Scheduled 23 November 2024)

A 3.1 GHz Defected Ground Transmission Line Microwave Sensor for Blood Glucose Estimation

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ABSTRACT: In the work presented in this paper, a microwave sensor is investigated for estimating the glucose level in the blood of a diabetic patient. The microwave sensor consists of a planar microstrip transmission line printed on one side of the substrate while four Circular Complementary Split Ring Resonators (CCSRR) arranged in compact beehive arrangement are etched out from the ground plane on the other side, thus forming a Defected Ground Transmission Line (DG-TL). It is well known that the dielectric properties of blood to a large extent depend on the intrinsic glucose concentration. Placing fingertip on the CCSRR cells is expected to disturb the electric field in the vicinity by changing the inductance-capacitance of the configuration and thus mirroring a change in the S-parameters of the transmission line. The changes, a shift in the resonance frequency and a change in the amplitude, is proportional to the dielectric strength of the adjacent medium which in turn is proportional to the blood glucose level. To mimic a human finger, a tiny glass container containing aqueous glucose solution is placed on the CCSRR configuration and by varying the glucose concentration; the changes in the S-parameters were observed. The sensor has planar dimensions of $60\,\text{mm} \times 20\,\text{mm}$ and offers a resolution of 0.75 MHz per mg/dL of glucose concentration. Simulations and measurements indicate the applicability of the design for identifying glucose levels in the blood.

1. INTRODUCTION

With the proliferation of diabetes around the world as a major life threatening disease, it has become imperative for researchers to find ways of detecting the disease and managing it at an earlier stage. The usual method of identifying the disease is by monitoring or measuring the glucose level in the bloodstream which for a healthy person should be in the range of 72 to 126 mg per deciliter before a meal and should be less than 153 mg per deciliter within 12 hours after the meal [1]. In the medical fraternity, several ways are available to actually monitor the glucose level in the blood; these methods can be classified as noninvasive, minimally invasive, and invasive [2]. In invasive methods, the blood sample is collected by pricking the finger, placing the finger on a strip to collect the blood which can be painful when being done in a repeated way as required for continuous monitoring of the blood glucose level; there is also a risk of infection. In the minimally invasive method, instead of a puncture going up to the blood vessels, the interstitial fluid present at the subcutaneous level is used for probing the blood glucose. The minimally invasive methods though successful in reducing the discomfort of the patient to some level are however quite expensive and may not be affordable to be used on a frequent basis. Hence, there is a demand among researchers to explore noninvasive methods of blood glucose detection and blood glucose monitoring.

Among the noninvasive methods reported in the literature, mention can be made of the optical methods, where scattering of light at various wavelengths or frequencies can be used to make a rough estimate of the glucose level in the blood. Similarly, monitoring saliva of the patient can also be used to identify the level of glucose in the blood.

Lately, microwave sensing techniques are gaining popularity in identifying the glucose in the blood. A correlation exists between the blood glucose level and the electrical properties of the blood such as dielectric strength and electric permittivity [3]. This fact can be used to design or set up planar configurations where the change in the permittivity of the medium reflects a change in the S-parameters which can be measured and can then indicate the amount of glucose in the blood. Typically, the microwave structures can be antennas or filters or transmission lines where the fingertip will be used to change the permittivity or dielectric strength of the medium surrounding the line. In [4], the proposed sensor utilizes an artificial transmission line consisting of 4 unit cells where each cell has an interdigital capacitor and an inductor grounded using a via hole. The biological tissue under test is placed over a coating on the capacitor-inductor configuration. The indicative parameter chosen was the magnitude and phase of S_{21} at the single frequency of 2 GHz. On the ground plane side, two SMA connectors are placed. The sensor proposed in [5] is an extended gap rectangular split ring resonator placed adjacent to a microstrip line. PTFE tubes carrying glucose solutions are placed over the Split Ring Resonator (SRR) and influence the amplitude and location of the resonant frequency. In [6], a patch sensor attached on the back side of a wrist watch and capable of continuously extracting the Interstitial Fluid (ISF) from the skin of the patient through a reverse iontophoresis process is proposed. In [7], the ground of a microstrip line is defected

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TABLE 1. Comparison of microwave sensors for blood glucose/permittivity measurement.

Ref [Year]	Configuration/Structure	Approx. Size	Measurement Range	Operating Frequency	Sensing Parameter	Resolution/Sensitivity
4 [2015]	MTL with series of interdigital capacitors and grounded inductors	20 mm × 5 mm	0–250 mg/dL	2.0 GHz	$\angle S_{21}$	Phase shift of 73° over range
5 [2017]	Extended gap square SRR adjacent to a MTL	20 mm × 15 mm	1–15 g/dL	1.863 GHz	*fr*	Sensitivity $(\Delta f/f_0 \Delta\varepsilon_r) = 0.3\%$
20 [2017]	Two U shaped resonators with tapered double-sided spiral SRR	18 mm × 12 mm	Dielectric constant 0–53	0.358 GHz	*fr*	Sensitivity $(\Delta f/f_0 \Delta\varepsilon_r) = 0.8\%$
9 [2018]	Printed Microstrip Interdigital capacitor	60 mm × 60 mm	1 g/dL–4 g/dL	4 GHz	*fr*	0.025 MHz/mg/dL
8 [2020]	Honey Cell SRR on the opposite side of MTL	66 mm × 20 mm	70–120 mg/dL	2.45 GHz	*fr*	0.94 MHz/mg/dL
11 [2020]	MTL with a tapered ground plane	50 mm × 20 mm	0–110 mg/dL	19 GHz	$\angle S_{11}$	0.2 degree/mg/dL
18 [2020]	MTL with dumb bell shaped defected ground	40 mm × 20 mm	2–12 mmol/dL	6.31 GHz	*fr*	–
19 [2020]	Power divider and two transmission lines coupled to two rectangular SRRs	18 mm × 15 mm	Dielectric constant 24–78	7.78 GHz	*fr*	Sensitivity $(\Delta f/f_0 \Delta\varepsilon_r) = 0.3\%$
10 [2021]	Branch line coupler with SRR	60 mm × 45 mm	70–450 mg/dL	2.395 GHz	*fr*	0.72 MHz/mg/dL
21 [2023]	Bandpass filter in SIW cavity	42 mm × 18 mm	92–141 mg/dL	9 GHz	*fr*	7.67 MHz/mg/dL
22 [2023]	Spurline Filters	35 mm × 32 mm	0–150 mg/dL	3.22 GHz	*fr*	0.233 MHz/mg/dL
23 [2023]	Microstrip Patch Antenna	70 mm × 70 mm	−1000 mg/dL	3 GHz	$\|S_{11}\|$	0.058 dB for every 100 g/dL
24 [2023]	CPW Transmission line rolled cylindrically	50 mm × 60 mm	73–213 mg/dL	2.4 GHz	*fr*	7.5 MHz/mg/dL
25 [2023]	Arrow-shaped Patch Antenna	35 mm × 13.5 mm	0–150 mg/dL	2.45 GHz	*fr*	3.4 MHz/mg/dL
26 [2023]	Microstrip Patch Antenna	45.25 mm × 53.75 mm	Dielectric constant 0–53	1.3 GHz	*fr*	9 MHz over the range
This work	MTL with a Circular SRR defected ground	60 mm × 20 mm	50–250 mg/dL	3.1 GHz	*fr*	0.75 MHz/mg/dL

by etching four hexagon-shaped CSRRs arranged in a compact honeycomb-shaped structure. Placement of the human finger on the CSRR alters the electric field in the vicinity and results in a variation in S parameters. The same authors extended the work to include Artificial Intelligence (AI) Principal Component Analysis (PCA) based detection in [8] for better performance. The design proposed in [9] is an inter-digital capacitor with 10 fingers printed on one side of an FR4 substrate. The sensor configuration proposed in [10] consists of a Branch Line Coupler (BLC) as the host transmission line and a split ring resonator embedded inside as the sensing area. Glucose solution applied on top of a cover glass placed on the sensing area represents the blood to be tested.

Some other microwave sensing techniques which can be used for blood glucose monitoring and detection are listed in [11–26]. A comparison of these sensors with the proposed work in terms of technique employed, size, permittivity range, operating frequency, and resolution achieved is given in Table 1. While comparing size of these sensors, it must be noted that some sensors are designed to touch the skin of the patient, some need a blood drop to be placed, and some allow for the placement of the finger.

The proposed sensor is a simple 50 Hz Defected Ground microstrip Transmission Line (DG-TL) where the defected ground structure is formed by etching out four Circular Complementary Split Ring Resonator (CCSRR) structures. From Table 1, it can be seen that the proposed sensor has a simpler structure along with a comparable resolution and offers an alternate design for future exploration and improvement.

2. DGS-TL DESIGN

The basic configuration of the microwave sensor to be utilized for blood glucose concentration estimation is shown in Fig. 1. As seen from the figure, the microstrip line of 1.5 mm width is printed on an FR4 substrate of length 60 mm, width 20 mm, and thickness 1.6 mm. The width of the line is calculated to offer 50 ohm impedance at the resonance frequency so as to enable perfect matching with Vector Network Analyzer (VNA) connectors. On the ground side of the microstrip line, two pairs of CCSRRs arranged in a compact configuration are etched to form a defected ground structure (DGS). A close-up view of the CCSRR is also shown in the figure.

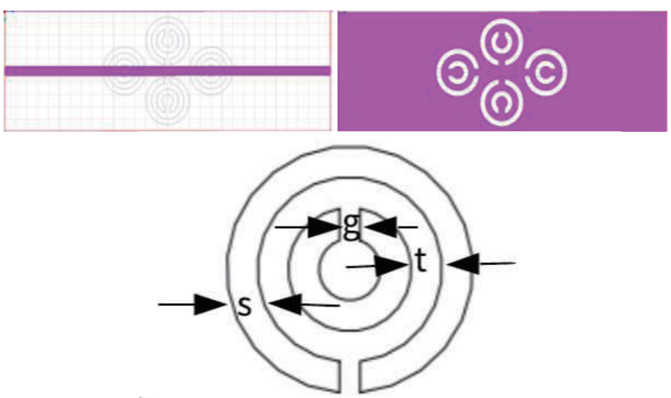

FIGURE 1. Basic configuration of the sensor.

The double split rings consist of two circular shape annular loops having a gap between them. The exterior ring of CSRR has an outer diameter $a = 8$ mm, ring width $s = 1$ mm, and split gap $g = 1$ mm. The inner ring has an outer diameter of 8.08 mm. Using parametric optimization feature of High Frequency Structure Simulator (HFSS), the distance between the rings 't' which controls the coupling is fixed at 1 mm.

The microwave sensor so designed envisages placement of finger of the diabetic patient over the CCSRR DGS etched on the ground plane. Doing so while the transmission line is connected to an RF source (VNA) disturbs the established electric field over the CCSRR thus creating alteration in the measured S_{21} characteristic. For simulation and measurement purpose in the present work, instead of an actual finger containing blood, a phantom in the form of a rectangular glass container containing aqueous glucose water solution is used. The container is meant to be placed on top of the CSRRs surface. This arrangement in an HFSS simulation environment is shown in Fig. 2.

The glucose water solution in the glass container is modeled as a medium having electrical characteristics (permittivity and conductivity) correlated to the glucose concentration in the distilled water. This correlation as approximated by the Cole-Cole equation and detailed in [4] is presented in Table 2.

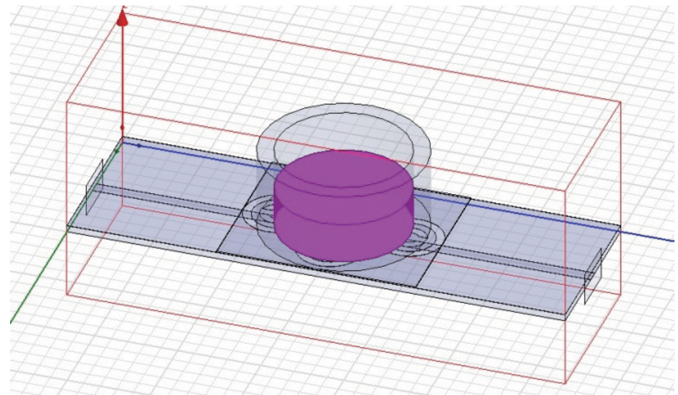

FIGURE 2. Glass container containing aqueous glucose solution to mimic finger of patient in HFSS environment.

TABLE 2. Electrical characteristics of aqueous glucose solution.

BGC [mg/dl]	Relative Permittivity εr	Equivalent Conductivty σe [S/m]
50	65.0547	1.4895
100	60.6768	1.4895
150	56.2990	1.4895
200	51.9211	1.4895
250	47.5433	1.4895

3. SIMULATION RESULTS

The sensor with the glucose water container placed on the top of the CCSRR configuration is tested for different glucose concentration levels ranging from 50 mg/dL to 250 mg/dL in Ansys HFSS, and the simulated S_{21} for different cases are shown in Fig. 3.

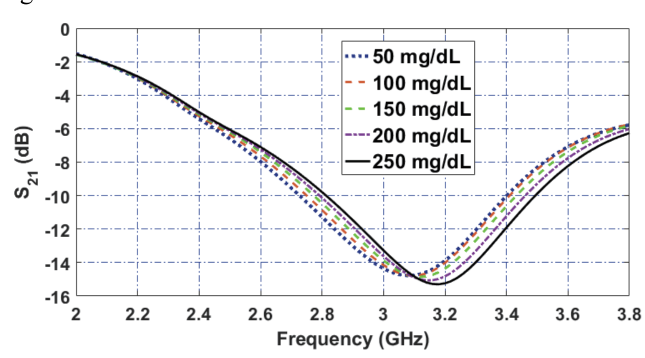

FIGURE 3. Simulated S_{21} for different glucose concentration levels.

As seen from this figure, a subtle variation in the resonance frequency and amplitude is noted with respect to the glucose concentration (and the correlated permittivity value) near 3.0 GHz.

In Fig. 4, the simulated electric field near the CCSRR region at the resonance frequency is shown for two cases: (a) when the transmission line with DGS has an empty container on top and

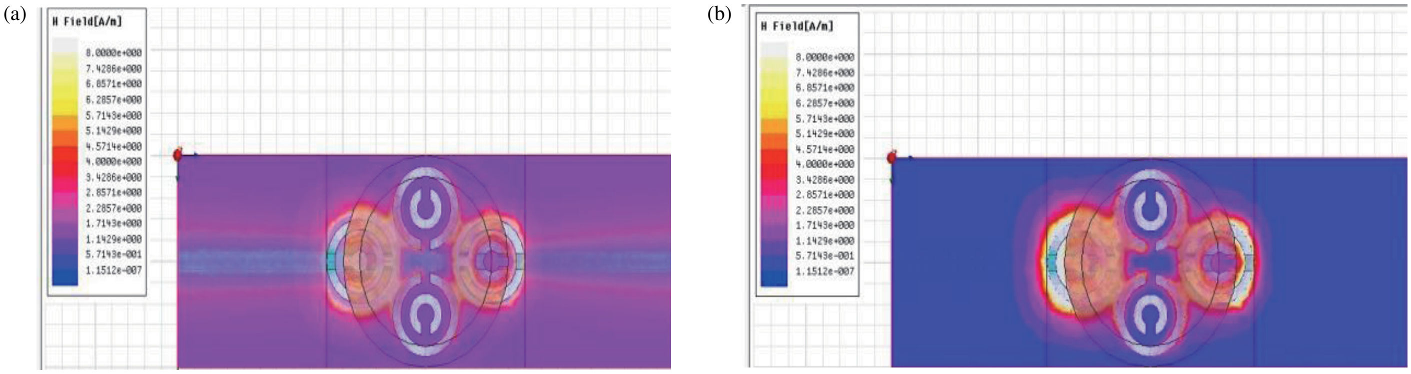

FIGURE 4. Simulated electric field near the CCSRR with (a) an empty container and (b) with a container containing aqueous glucose solution.

(b) when the container on top has the glucose solution. It can be seen from this figure that the presence of glucose solution in the container allows for a higher concentration of the electric field near the split ring resonators, showing the ability of the solution to modify the transmission characteristics.

4. MEASUREMENT RESULTS

A photograph of the fabricated prototype of the microwave sensor with the optimized dimensions is shown in Fig. 5 while the experimental setup with a glucose solution containing container placed on top of the DG-TL connected to a Nano VNA is shown in Fig. 6.

The measured S_{21} values for different glucose concentration levels (same levels as those chosen for simulation) are shown in Fig. 7. Again, as with the simulated case, a subtle variation in the resonance frequency and amplitude in the S_{21} value near 3 GHz is observed. A plot of the resonance frequency location (simulated and measured) with respect to the glucose concentration value is given in Fig. 8 while a plot of the S_{21} amplitude near 3 GHz with respect to different glucose levels is given in Fig. 9. While the resonance frequency locations of both simulated and measured cases show near agreement, the S_{21} amplitude near 3 GHz has a higher value for the simulated result than for the measured result. This may be attributed to general modeling inaccuracy of the glucose solution and other fabrication imperfections. The general trend observed is that with an increase in glucose concentration, the resonance shifts to higher frequencies, and S_{21} amplitude in dB becomes less neg-

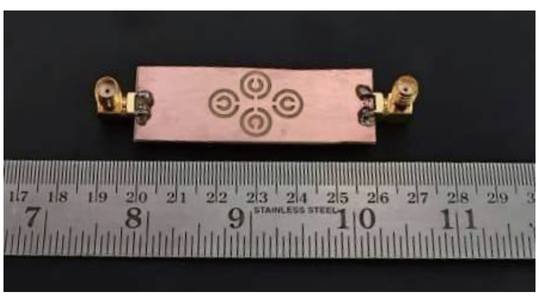

FIGURE 5. Fabricated sensor.

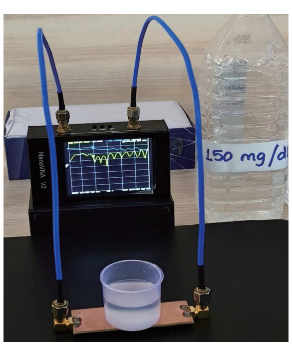

FIGURE 6. Experimental setup for estimation of glucose concentration.

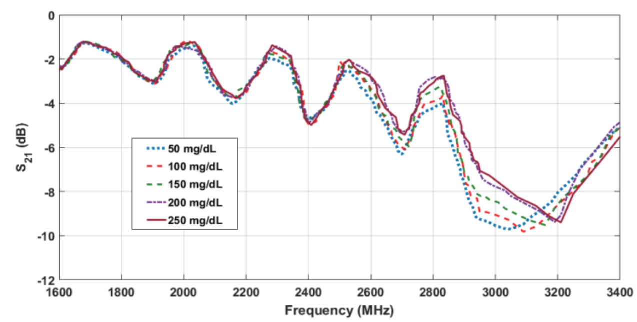

FIGURE 7. Measured S_{21} for different glucose concentrations.

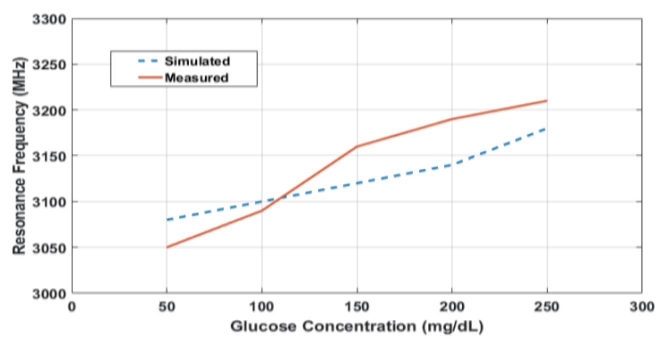

FIGURE 8. Variation in the resonance location (frequency) with respect to the glucose concentration.

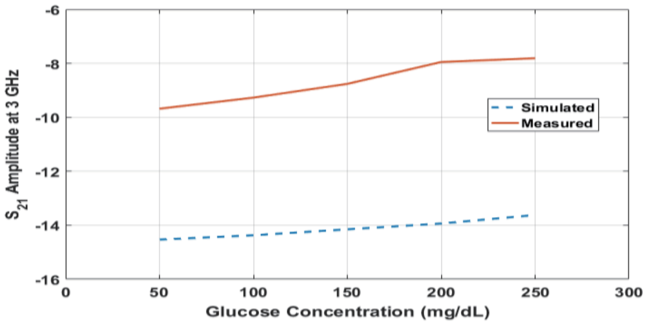

FIGURE 9. Variation in the S_{21} amplitude near 3 GHz with respect to the glucose concentration.

ative ($|S_{21}|$ increases). Either or both these trends can be used along with an Artificial Neural Network (ANN) or a Support Vector Machine (SVM) based classifier to estimate the glucose concentration in the water (experiment) or blood (actual case study).

5. CONCLUSION

In this paper, a simple to construct and cost effective microwave sensor is presented for noninvasive estimation of glucose concentration in the blood of a diabetic patient. The sensor having dimensions of 60 mm $\times$ 20 mm consists of a 50 Hz transmission line embedded on a defected ground. DGS is obtained by etching four circular, complementary split ring resonators from the ground plane. In the investigations reported, a small glass container containing aqueous glucose solution with varying concentration mimics the human finger actually envisaged to be used. The sensor offers a resolution of 0.75 MHz per mg/dL of glucose concentration. Simulated and measured results indicate the possibility of using both the resonance frequency location and amplitude to make a satisfactory estimation of the blood glucose concentration.

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