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A Non-Invasive Method of Monitoring Glucose in Blood Using a Planar Yagi-Uda Antenna and Microstrip Filter

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***Abstract*—This work presents a non-invasive method to determine the glucose levels in blood samples using a planar Yagi-Uda antenna and a novel microstrip filter. The proposed antenna operates at 5.5 GHz and exhibiting uni-directional pattern giving a maximum gain of 6.74 dBi at the operating band. A commercially available and low-cost FR-4 substrate of dimensions 30 mm×40 mm×1.6 mm is used as a dielectric substrate. A finger phantom resembling a human finger is designed in the simulation environment, which consists of bone, skin, blood, fat as different layers. The glucose concentration is varied from 0 mg/dL to 500 mg/dL and the shifts in the frequencies are observed by keeping the phantom at various locations surrounding the antenna. A good frequency shift of 26 MHz is observed when the phantom is placed below the antenna. A good similarity is observed between the simulation and measurement results. Also, a novel microstrip filter, operating at 5.5 GHz, is developed, and the frequency shifts are studied by keeping a finger phantom at the top of the filter. The designed filter is shown to give a maximum frequency shift of 4 MHz when the glucose concentration changes from 250 mg/dL to 500 mg/dL. This study is supported by analysing transmission coefficient parameters and group delay characteristics.**

***Index Terms*—Blood; Glucose levels (mg/dL); Microwave sensor; Microstrip filter; Non-invasive method; Yagi-Uda antenna.**

I. INTRODUCTION

Diabetes is one of the main chronic diseases characterised primarily by very high sugar levels in the blood over a long period of time [1], [2]. The general practice in measuring glucose levels is by employing the methods like shrill or glucose meter and these methods come under invasive techniques [3], [4]. These methods cause pain to the patient as needle is to be inserted into the patient's skin in the body. Recent study suggests that many of the diabetic patients do not visit hospitals due to the pain caused by the needle insertion. This is a major problem in the medical field for doctors till a novel method known as non-invasive method is invented. In this method, microwave technology or methods are used for measuring glucose concentration levels in the patient's blood samples [5]–[10]. These methods include the use of microwave devices and components like filters and antennas etc. These methods gained much popularity nowadays, owing to the ease of implementation and absence of pain and fear to the patient [11]–[16].

Buford, Green, and McClung [17] proposed a novel microwave sensor, and another latest method of sensing pressure is discussed in detail in [18]. In another method, study on dielectric properties of the material is used for glucose monitoring as developed by Deshmukh and Ghongade [19]. Use of animal tissue is another method for glucose monitoring as human's and animal's tissues resemble in many ways and this method was invented by Cano-Garcia *et al.* [20]. The latest literature discusses several novel methods of identifying the presence of glucose in human blood samples using microwave technology [21]–[27]. In the recent technology, meta-materials are proved to be highly advantageous in terms of device size and sensitivity in glucose monitoring [28]. The current research provides different novel methods of monitoring glucose in human blood samples using microwave components like filters, antennas etc. [29]–[34]. In the recent studies, microstrip filters have also been shown to be an effective means of finding glucose concentrations [35]–[36]. Flash glucose monitoring (FGM) is one of the current popular methods, where glucose levels in interstitial fluid are monitored with a sensor inserted under the skin and finger-pricking is required to test blood glucose under these circumstances, when glucose levels are rapidly changing. However, this method causes infection, allergic reactions, skin reactions, redness, itching and rash, sensor-insertion events, sensor adhesive or site reactions. Therefore, in the

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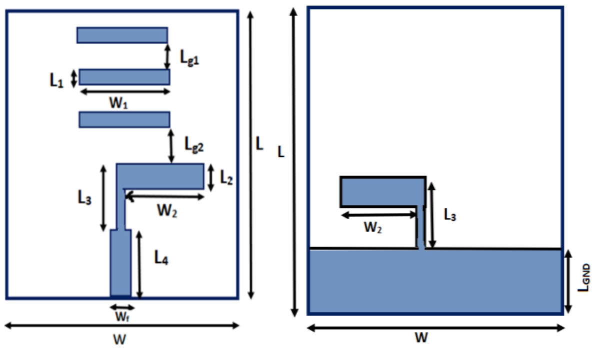
present research work, an effective, simple, non-invasive, compact, and sensitive microwave antenna sensor is proposed and designed.

As discussed earlier, the use of microwave antennas or microstrip filters proved to be the effective methods in glucose monitoring. In the present discussion, the design and development of novel Yagi-Uda antenna and microstrip filter operating at 5.5 GHz for monitoring glucose levels in human blood samples are presented. A finger phantom resembling real human finger is designed and developed in simulating environment. The designed antenna can measure the glucose concentration in the blood samples with more sensitivity and accuracy. The remainder of the paper is discussed as follows. Section II presents the planar Yagi-Uda antenna design and the study of the results. Section III discusses the modelling of a finger phantom and associated studies on frequency shifts for different positions of the finger model and various glucose level concentrations. Section IV presents the design of the microstrip filter for glucose concentration in the blood samples. Section V concludes the work.

II. ANTENNA DESIGN

Figure 1 presents the design model of the proposed Yagi-Uda antenna for evaluating glucose concentration. The proposed Yagi antenna consists of three parasitic strips with an inverted L-shaped stub as shown in Fig. 1(a). Another similar type of stub is employed on the ground plane as shown in Fig. 1(b). The proposed antenna's dimensions are mentioned in Table I and are optimised so that the antenna operates at 5.5 GHz. The prototype of the fabricated proposed antenna is given in Fig. 2, representing the view of both top and bottom views of the proposed antenna.



(a) (b)

Fig. 1. Proposed antenna: (a) Top view; (b) Bottom view.

TABLE I. DIMENSIONS OF THE PROPOSED ANTENNA.

Parameter	Dimension (mm)
L	40
W	30
L_1	2
L_2	3.5
L_3	8
L_4	10
L_{g1}	4
L_{g2}	6
W_1	10
W_2	11
L_{GND}	11
W_f	3

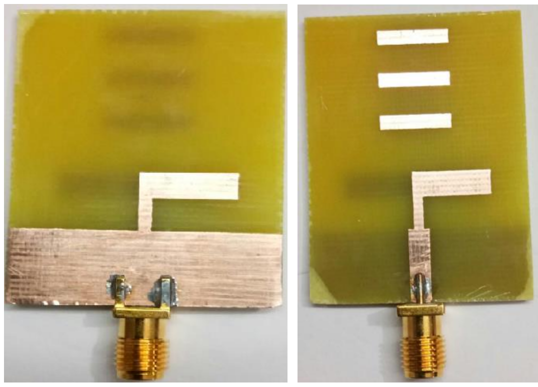

(a) (b)

Fig. 2. Fabricated prototype of the proposed antenna: (a) Top view; (b) Bottom view.

The comparison of measured results with simulated results is given in Fig. 3, where both the results are observed to be well matched.

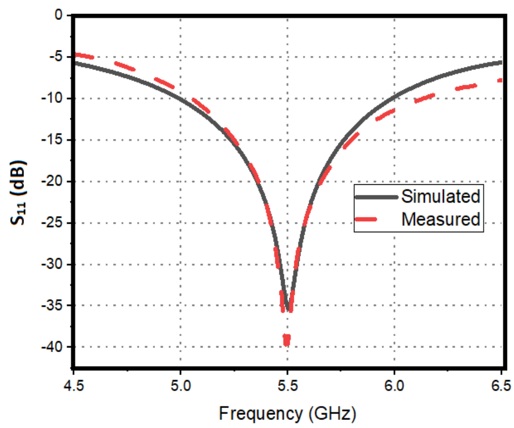


Fig. 3. Simulated and measured S_{11} (dB) of the proposed antenna.

The simulated and measured XY & YZ plane radiation patterns are shown in Fig. 4. From Fig. 4, it is observed that the fabricated antenna gives good directional properties at 5.5 GHz, which is the desired characteristic for the antenna to be used for measuring glucose concentrations in finger phantoms. As the antenna sensor is placed near to the finger, the radiation pattern directly penetrates into the patients' blood in order to predict the glucose concentration. A peak gain of 6.74 dBi is observed by analysing the 3-D radiation pattern as given in Fig. 5, which is very much desired in glucose monitoring. The surface current distribution of the proposed antenna is shown in Fig. 6, when the antenna is operating at 5.5 GHz.

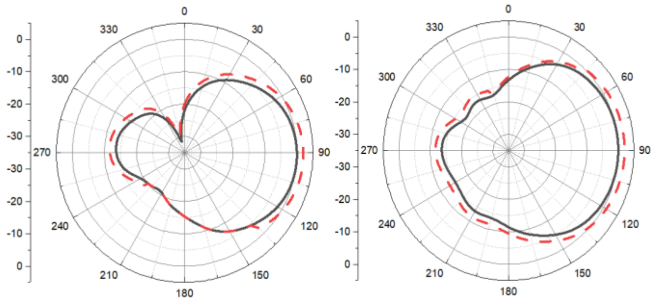

(a) (b)

Fig. 4. Simulated and measured radiation patterns at 5.5 GHz in (a) XY-plane and (b) YZ-plane.

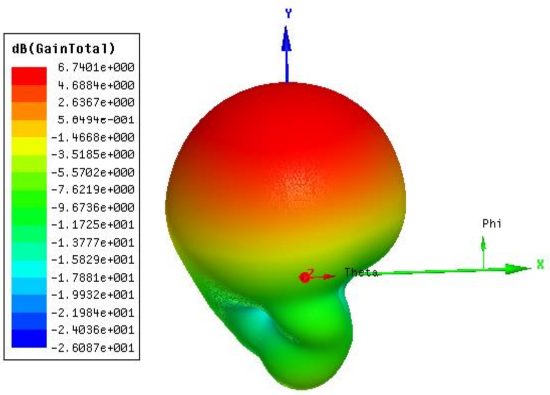


Fig. 5. 3D-radiation pattern at 5.5 GHz.

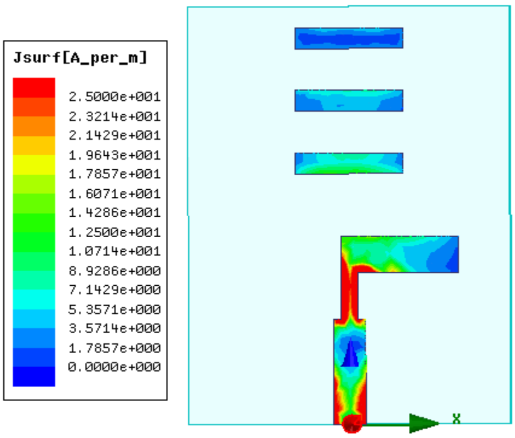


Fig. 6. Surface current distribution at 5.5 GHz.

The figure shows considerable flow of current on the parasitic elements indicating that the proposed antenna acts as a good radiator in the desired band of operation.

III. EVALUATION OF GLUCOSE CONCENTRATION USING SIMULATED FINGER PHANTOM

As mentioned earlier, the main objective of the work is to evaluate the glucose concentrations in the human blood samples without causing pain which usually occurs in needle insertion methods like invasive method. In order to accomplish this, a human finger is designed in the simulation environment, which resembles the structure of a real human finger. Various layers of the finger such as skin, fat, blood, and bone are modelled using dielectric materials of different dielectric constants [29]. The middle layer of the phantom is considered as bone in the simulation environment. Debye model or Cole-Cole model is used in order to calculate the dielectric constant values of various layers of the phantom. In general, Cole-Cole model is used in many cases. As per the Cole-Cole model, the dielectric constants can be estimated using (1)

$$\hat{\varepsilon}(w) = \varepsilon_c'(w) - j\varepsilon_c''(w) = \varepsilon_\infty + \sum_n \frac{\Delta\varepsilon_n}{1+(j\omega\tau_n)^{(1-\alpha_n)}} + \frac{\sigma_i}{j\omega\epsilon_0}, \quad (1)$$

where, $\varepsilon_c'(\omega)$ is the frequency-dependent dielectric constant, $\Delta\varepsilon_n$ is the magnitude of the dispersion, α_n is the parameter that allows the broadening of the dispersion, ω is the angular frequency, $\varepsilon_c''(\omega)$ is the frequency-dependent dielectric loss, ε_∞ is the high frequency permittivity, n is the order of the Cole-Cole model. The, conductivity, dielectric constant, loss tangent at 5.5 GHz and dimensions [32] of all layers of the phantom are given in Table II. The dielectric constants and the loss tangent of the blood for various glucose concentrations at 5.5 GHz are shown in Table III as considered or mentioned in [30].

TABLE II. DIELECTRIC CONSTANT, LOSS TANGENT, AND DIMENSIONS OF THE ANTENNA AT 5.5 GHZ.

Finger parameters	Skin	Fat	Blood	Bone
Dielectric constant value (ε_r)	34.5	5	64.5	10
Loss tangent	0.255	0.245	0.375	0.37
Dimension	S4	S3	S2	S1

TABLE III. DIELECTRIC CONSTANT AND CONDUCTIVITY VALUES FOR DIFFERENT GLUCOSE CONCENTRATIONS.

Glucose concentration (mg/dL)	5.5 GHz	
	ε_r	Loss tangent
0	64.5	0.39
250	64	0.38
500	63.5	0.37
750	63	0.37
1000	62.5	0.36

The phantom is kept at various positions around the antenna, like at the bottom of the feed line, at the top of the feed line, at the top of the directors, at the bottom of the radiating element as shown in Fig. 7(a), at the top of the radiating element etc. The frequency shift and the change in the reflection coefficient values are studied by changing the glucose concentration with glucose levels variation from 0 mg/dL to 500 mg/dL and the results are presented for the useful and important cases here, where the desired frequency shifts are obtained.

In the initial case, the glucose concentration is varied from 0 mg/dL to 500 mg/dL by keeping the phantom at a distance of 0.5 mm beneath the antenna and the resulting scattering parameters are generated as shown in Fig. 7(b). The resonant frequencies are observed to be gradually shifting on right hand side as the glucose concentration increases or changes from 0 mg to 500 mg/dL. For 0 mg/dL glucose concentration, the sensor resonates at 5.524 GHz. A minimum shift of 3 MHz is observed for each step on raise in glucose level i. e from 0 mg/dL to 125 mg/dL, from 125 mg/dL to 250 mg/dL, and from 250 mg/dL to 500 mg/dL. As the obtained shifts are mapped to glucose concentration levels, the proposed sensor can be used practically for measuring glucose levels in patient's blood samples. In the second case, the phantom is placed at 1 mm below the sensor and the obtained S_{11}-parameters are shown in Fig. 7(c) for different levels of glucose concentrations. This case is proved to be more prominent as a maximum shift of 26 MHz is obtained as the glucose varies from 250 mg/dL to 500 mg/dL. In the third case, the phantom is placed without any gap between the sensor i.e. at 0 mm and the obtained S_{11}-parameters are shown in Fig. 7(d), from which it is observed that almost no frequency shift is observed. Hence, this case is not useful in predicting glucose levels in blood samples. The different cases, of the resultant resonant frequencies obtained by varying glucose concentration and the resulting magnitudes of S_{11}-parameters are given in Table IV.

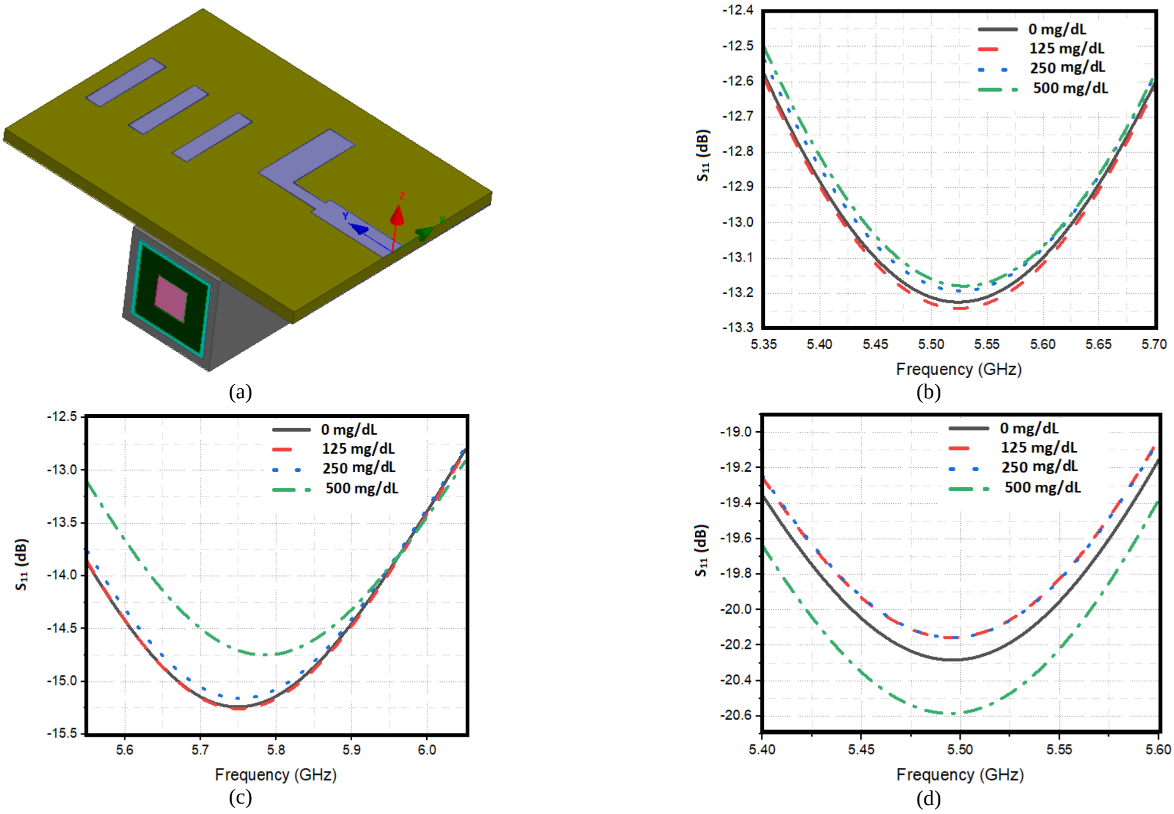


Fig. 7. (a) Finger on bottom of antenna; Variation of S_{11}-parameters of the antenna for different glucose concentrations when the finger phantom is placed at: (b) bottom of antenna at 0.5 mm, (c) bottom of antenna at 1 mm, and (d) bottom of feed at 0 mm.

TABLE IV. SUMMARY OF FREQUENCY SHIFTS FOR DIFFERENT FINGER POSITIONS.

	0 mg/dL	**125 mg/dL**	**250 mg/dL**	**500 mg/dL**
	Frequency Shift (MHz)	**Frequency Shift (MHz)**	**Frequency Shift (MHz)**	**Frequency Shift (MHz)**
Bottom of Antenna at 0.5 mm	-	6	3	4
Bottom of Antenna at 1 mm	-	**5**	**5**	**26**
Bottom of feed at 0 mm	-	0	0	0

IV. DESIGN OF MICROSTRIP FILTER FOR GLUCOSE CONCENTRATION EVALUATION

In the previous section, the design of a novel Yagi-Uda antenna was presented to monitor glucose concentration in human blood samples. In this section, the design of a novel microstrip filter for the same objective is presented and discussed. To predict glucose concentration in blood samples, a microstrip filter of size 15×25 mm2 is considered, as shown in Fig. 8.

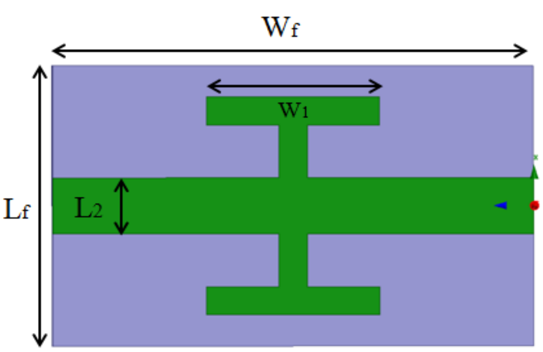


Fig. 8. Proposed Microstrip Filter resonating at 5.5 GHz.

The length (L_f) and width (W_f) of the patch filter are 15 mm and 25 mm, respectively, with W_1 as 9 mm and L_2 as 3 mm. This filter is formed on a low-cost FR-4 substrate with dielectric constant of 4.4. The proposed filter resonates at 5.5 GHz with a reflection coefficient value of -27.888 dB and transmission coefficient value of -0.9322 dB, as shown in Fig. 9.

The main objective of this research work is to design a microstrip filter that can measure glucose concentration in the blood. To achieve this, a finger phantom model is developed considering the structure of a real human finger [22]. Various layers of the finger, such as skin, fat, blood, and bone, are modelled using dielectric materials of different dielectric constants. Different layers are considered in square shape viz; bone layer as of size 4×4 mm^2, blood layer as of size 9×9 mm^2, fat layer as of size10×10 mm^2, and skin layer as of size 12×12 mm^2. The length of the finger phantom is chosen to be 20 mm. These values are optimised resembling a real human finger so that the proposed microstrip filter sensor can be conveniently used for real-time glucose monitoring applications. The finger phantom is placed on top of the microstrip filter as shown in Fig. 10(a). For different values of glucose concentrations from 0 mg/dL to 500 mg/dL, the S_{11}-parameters are obtained and the corresponding shifts are observed as shown in Fig. 10(b). From the graph, it is observed that the shifts in the frequency are observed as the glucose concentration is varied from 0 mg/dL to 500 mg/dL. The shifts observed for various glucose concentrations are 2 MHz, 2 MHz, and

4 MHz as shown in Table V.

TABLE V. SUMMARY OF RESONANT FREQUENCIES, S-PARAMETERS AND GROUP DELAYS.

Glucose level	**Resonant frequency (GHz)**	**Fre. Shift (MHz)**	**S_{11} (dB)**	**S_{21} (dB)**	**Group delay (ns)**
0 mg/dL	5.214	-	-18.9719	-7.22192	0.179867
125 mg/dL	5.216	2	-18.9696	-7.21817	0.179985
250 mg/dL	5.218	2	-18.9685	-7.21447	0.180103
500 mg/dL	5.222	4	-18.9712	-7.20609	0.180344

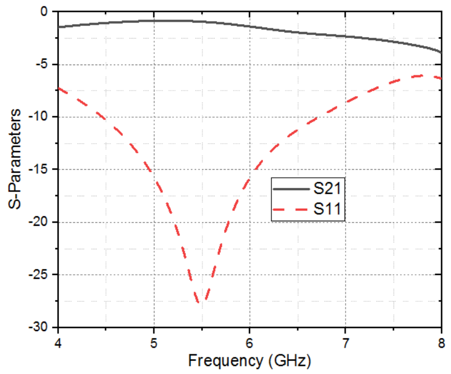
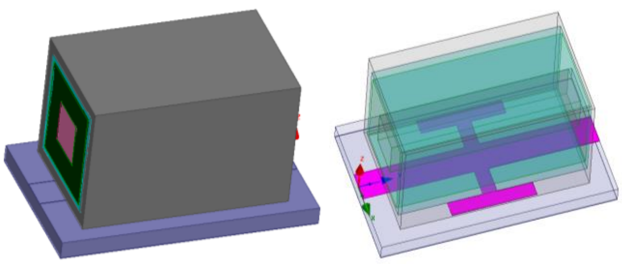
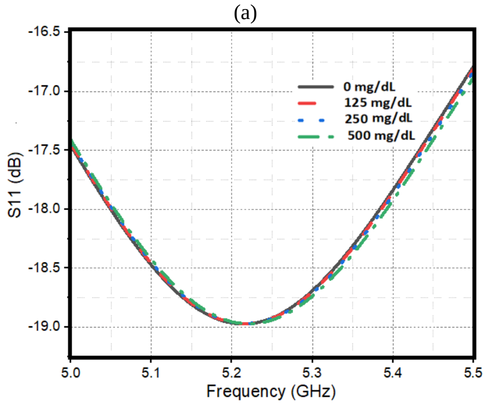


Fig. 9. S-parameters of the proposed microstrip filter.



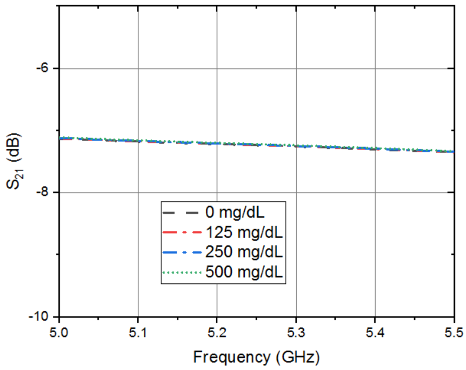
(a)



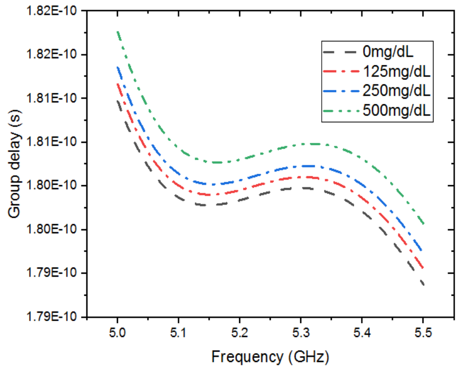
(b)

Fig. 10. Finger phantom placed over top of the filter: (a) Top view; (b) Variation of S-parameters w. r. t glucose concentration.

The frequency shifts obtained can be used to monitor glucose concentration in the blood samples. The transmission coefficient parameters and group delay curves are shown in Fig. 11, from which it is observed that these two parameters are also changing with respect to the variations in glucose concentrations.



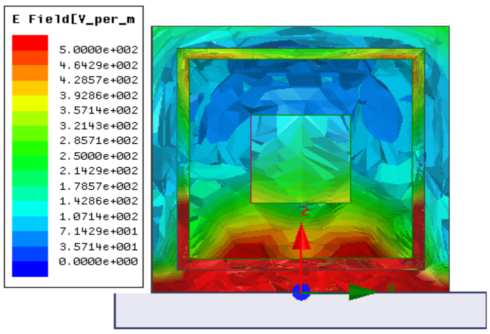
(a)



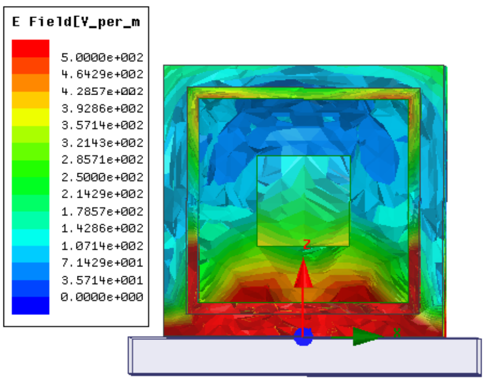
(b)

Fig. 11. S_{21}-parameters and group delay for different glucose Concentrations.

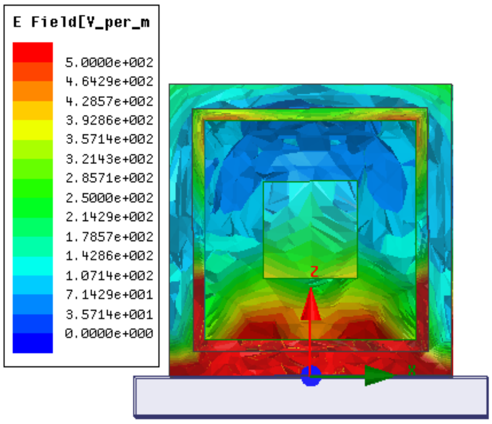
When the glucose concentration is varying from 0 mg/dL to 500 mg/dL, the transmission coefficient and group delay are observed to vary and these changes can be mapped for glucose monitoring. The E-field distribution of the finger phantom for different cases of glucose concentrations is given in Fig. 12.



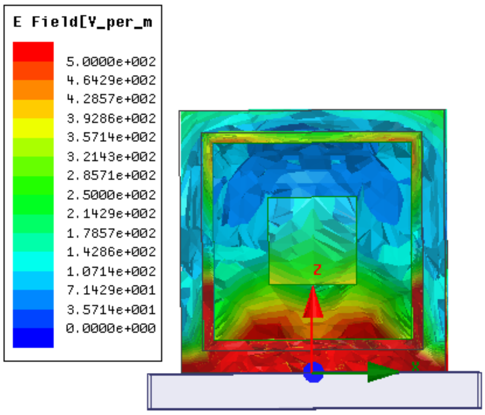
(a)



(b)



(c)



(d)

Fig. 12. E-field distribution with finger phantom placed over the top of the filter for (a) 0 mg/dL, (b) 125 mg/dL (c) 250 mg/dL, and (d) 500 mg/dL.

From the given figures, it is observed that electric fields are observed to be varying when the phantom is placed over the sensor. More variation of the electric field on the filter is required for glucose-level measurements. This is due to the fact that more variation of the fringing fields on the filter results in a considerable change of the dielectric constant of the filter, which in turn gives a considerable frequency shift when the finger phantom is placed close to the filter.

V. CONCLUSIONS

This work presented the design and development of a novel planar Yagi-Uda antenna resonating at 5.5 GHz. The antenna gives a maximum gain of 6.74 dBi, which makes it suitable for evaluating the glucose level concentrations in the blood. A finger phantom resembling a human finger is designed in simulation software, which consists of bone, skin, blood, fat as different layers. The glucose concentration is varied from 0 mg/dL to 500 mg/dL and the shifts in the frequencies are observed by keeping the phantom at various locations surrounding the antenna. A good frequency shift of 26 MHz is observed when the phantom is placed below the antenna (performance comparison is shown in Table A-I). Also, a novel microstrip filter resonating at 5.5 GHz is developed. The frequency shifts are studied by keeping a finger phantom at the top of the filter for various cases of glucose concentration. The designed filter is shown to give a maximum frequency shift of 4 MHz when the glucose concentration changes from 250 mg/dL to 500 mg/dL. The study is supported by analysing transmission coefficient parameters and group delay characteristics. It can also be concluded that the proposed method for measuring glucose in blood samples is suitable for real-time applications.

APPENDIX A

TABLE A-I. PERFORMANCE COMPARISON OF PROPOSED WORK.

Ref.	Technology	Operating frequency (GHz)	Frequency shift	Glucose variation (mg/dL)
[31]	Non-invasive finger placed on planar resonator	1.8	1.34 MHz	0–16000
[32]	Non-invasive finger placed on dielectric resonator	4.7	2.81 KHz	0–16000
[33]	Invasive method by extracting fluids	5.41	62.5 KHz	0–8000
[34]	Microstrip antenna sensor	2.5 to 18	-	0 %–80 % of solution
[35]	Non-invasive wearable split ring resonator	1.5	5 KHz	0–4000
[36]	Interdigitated capacitor (IDC) resonator-etched (CPW)	2.46	2 MHz	0–8000
This work	Non-invasive method using planar Yagi-Uda antenna/ Microstrip Filter	5.5	26 MHz/ 4MHz	0–500

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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