Research Article

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A novel compact highly sensitive non-invasive microwave antenna sensor for blood glucose monitoring

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Abstract: In the present work, a novel compact and highly sensitive microwave antenna sensor at 2.45 GHz is proposed for evaluating glucose concentration in blood. The antenna is printed on an FR-4 substrate of compact dimensions 35 mm × 13.5 mm × 1.6 mm. A human finger phantom model is constructed in the EM simulation high frequency structure simulator environment consisting of skin, blood, fat, and bone layers. In the study, finger models with various shapes like rectangular, cylindrical, and ellipsoid are considered, and the results are compared. The glucose concentration is changed from 0 to 500 mg/dL, and the corresponding shift is evaluated by keeping the finger phantom at different locations near the antenna. The frequency shifts obtained in the designed experiment are used to evaluate glucose concentration in blood samples. In this work, a minimum and a maximum frequency shift of around 1.25 and 5 MHz, respectively, are observed when the finger phantom is placed at the top of the radiating element. Simulated antenna results are found to be in good agreement with the measured results. The developed method is validated with a two-antenna model by calculating time delay and isolation for different glucose concentrations. An experiment of placing a real human finger around a fabricated antenna presents good correspondence with the simulation results.

Keywords: blood, finger phantom, glucose monitoring, microwave sensor, non-invasive, slotted patch

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1 Introduction

Diabetes is one of the major chronic diseases mainly characterized by very high sugar levels in the blood for a long time [1,2]. The common method to measure glucose levels is using a finger prick and glucometer, which is known as an invasive method [3,4]. However, the invasive methods cause pain to the patient, as blood samples are to be suctioned/pricked each time. One solution for this problem is a non-invasive method, where microwave filters or antennas are used to monitor glucose levels in the blood samples [5–10]. Recently, microwave antennas have found various biomedical applications like body wearable devices [11].

In this non-invasive method, sensors in the form of antennas or RF filters are involved in measuring glucose concentration. In non-invasive techniques, popular methods of detecting glucose concentration levels are by using microstrip resonator (filter) technique or microstrip antenna techniques. Also, these are prominently preferred in the medical field due to no risk of ionization, deep penetration, and immune to temperatures and other disturbances.

In detecting glucose concentration in blood samples, a novel design of sensors with high sensitivity is required to be designed. Various sensors like pressure sensor [12] and a narrow band antenna sensor [13] with highly sensitive characteristics are discussed in the literature. Dielectric properties of various skin layers play an important role in the design of glucose-measuring sensors [14–17]. In the study of Nella *et al.* [18], a novel method of precise measurement of blood glucose using planar Yagi-Uda antenna and microstrip filter was presented. In the study of Sbrignadello *et al.* [19], a review of different types of novel sensors for glucose monitoring is presented in an effective manner. The use of metamaterials is another choice for detecting glucose, as detailed in the study of Islam *et al.* [20]. The FMCW milli-meter wave RADAR sensor is utilized for detecting glucose concentration in the blood samples [21]. Similarly, various other methods like the coplanar sensor method [22], multiple split ring resonator [23], chipless tag split ring resonator, [24] *etc.*, are

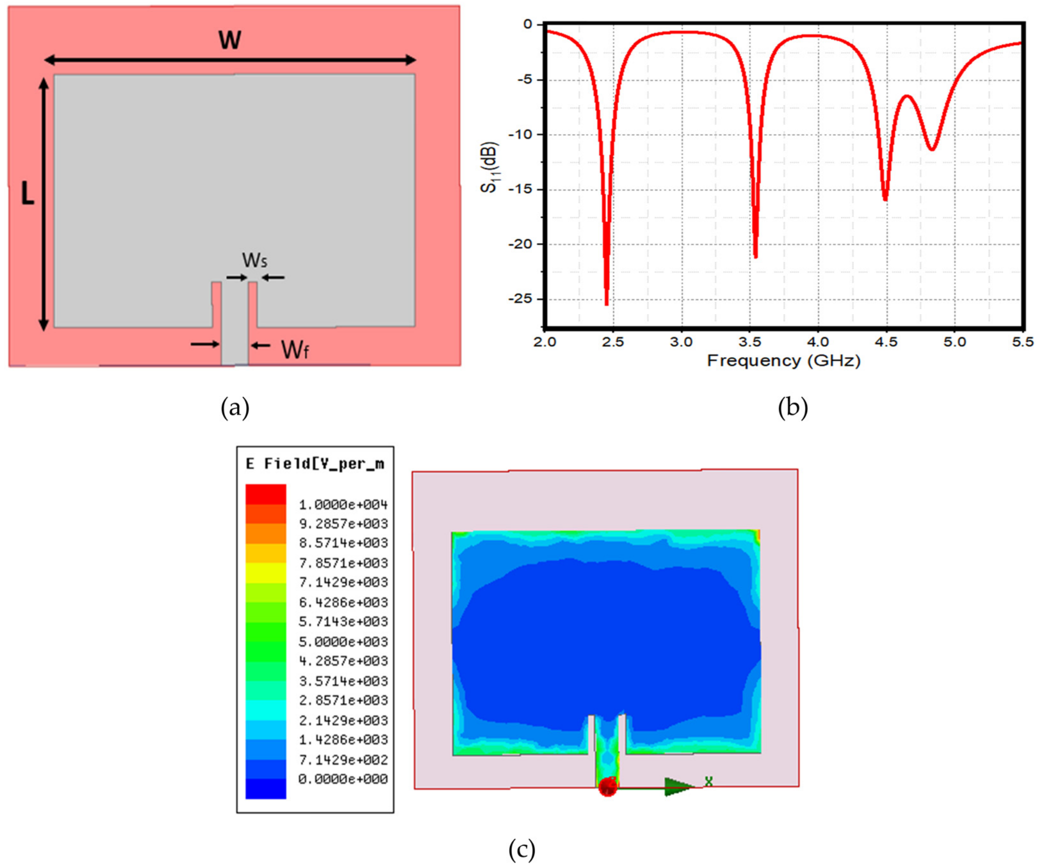


Figure 1: Patch antenna: (a) geometry, (b) S_{11} parameters, and (c) E-field distribution at 2.45 GHz.

employed for glucose level monitoring. In all these methods, glucose concentration in blood samples is measured by mapping various layers of skin with different dielectric constants and thus by measuring corresponding frequency shifts, which occur due to the variation of electric fields of the sensor. In the process of glucose monitoring, sensitivity and compactness of the sensor are the main issues to be considered. Hence, this work mainly focuses on the design and development of a novel sensor with compactness and giving better sensitivity characteristics. The proposed sensor operates at 2.45 GHz without phantom loaded, and it shifts near to 5 GHz when the phantom is placed over the sensor. In the existing literature, several antennas operating at the 2.45 GHz band, covering the ISM applications, are presented [25–28].

The proposed microwave sensor is taken on a low-cost FR-4 substrate of dimensions 35 mm × 13.5 mm × 1.6 mm with a dielectric constant value of 4.4 and a loss tangent of 0.02. The proposed sensor gives a quasi-linear shift in the frequency of S_{11} with the variation of glucose concentration, thus giving more sensitivity as the glucose differs from 0 to 500 mg/dL. The proposed antenna design and sample human finger are developed in the finite-element method (FEM) solver high frequency structure simulator (HFSS).

The rest of this article is discussed as follows. Section 2 presents an evolution of the proposed antenna design and associated glucose concentration study. Also, in this section, a four-layer finger phantom model is introduced. These layers are skin, blood, fat, and bone. Each has different thicknesses and dielectric constants. As the concentration of glucose changes, the blood dielectric constant is varied, and the S_{11} parameters are obtained. Section 3 discusses measured reflection coefficient parameters by placing the finger of a healthy person and the finger phantom at various positions on the antenna to validate the proposed phantom model and illustrate that the model is a replica of a real human being finger to a far extent. Section 4 concludes the work.

2 Antenna design and glucose concentration monitoring

2.1 Basic rectangular patch antenna

In this design process of a highly sensitive microwave antenna sensor, a basic rectangular patch antenna of size

50×40 mm^2 is initially considered, as shown in Figure 1(a). Feed width (W_f) is 3 mm, and slit width (W_S) is considered as 1 mm. The width (W) and length (L) of the patch antenna are 40 mm and 28.15 mm, respectively. The operating resonant frequency of the antenna is determined using the design basic design equations given in ref. [29]. This antenna is formed on a low-loss FR-4 substrate with a dielectric constant of 4.4. This antenna resonates at 2.45 GHz with harmonics at 3.5 and 5.5 GHz, as shown in Figure 1(b). The distribution of the E-field is shown in Figure 1(c), from which it is observed that almost no variation of filed current is observed throughout the antenna except at the outer edges.

2.2 Design of finger phantom for glucose monitoring

The main objective of this research work is to design an antenna 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, as shown in Figure 2 [22]. In the study of Cebedio *et al.* [22], it is considered that a rectangular finger phantom is more suitable for glucose concentration evaluation in blood samples. 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 S1 of size 4×4 mm^2, blood layer as S2 of size 9×9 mm^2, fat layer as S3 of size 10×10 mm^2, and skin layer as S4 of size 12×12 mm^2. The length (***L***) of the finger phantom is considered as 30 mm with height $H = 12$ mm. Dimensions and dielectric constants of various layers of the finger phantom are given in Table 1 [9].

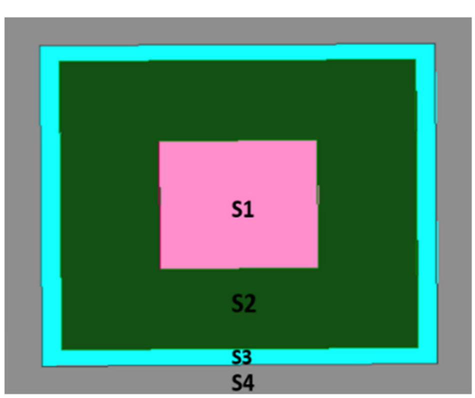
Table 1: Dielectric constant, loss tangent, and dimensions of the finger phantom at 2.45 GHz [9]

Finger parameters	Skin	Fat	Blood	Bone
Dielectric constant value (ε_r)	38	6	59	11.5
Loss tangent	0.32	0.18	0.38	0.35
Dimension (mm^2)	S4 (12 × 12)	S3 (10 × 10)	S2 (9 × 9)	S1 (4 × 4)

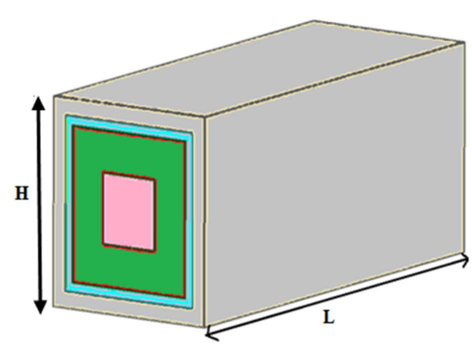
In biomedical applications, various methods are described to model various layers in the body and to obtain the equivalent dielectric constant values. Dielectric constant values of various tissues are calculated using various models like the Debye model [30] or the Cole–Cole model, and in general, the latter model is preferred in many cases [16]. This method is proven to be the more accurate method in modelling the dielectric values of various tissue layers as this method gives more correlation between electrical properties of blood plasma and glucose concentrations. As per the Cole–Cole model, the dielectric constant value can be estimated using the following equation:

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

where ω is the angular frequency, $\varepsilon_c'(\omega)$ is the frequency-dependent dielectric constant, $\varepsilon_c''(w)$ is the frequency-dependent dielectric loss, ε_∞ is the high-frequency permittivity, $\Delta\varepsilon_n$ is the magnitude of the dispersion, n is the order of the Cole–Cole model, α_n represents the broadening of dispersion, σ_i is the ionic conductivity, and τ_n is the relaxation time constant.



(a)



(b)

Figure 2: Finger phantom model: (a) top view and (b) isometric view.

Table 2: Dielectric constant values of the finger phantom at 2.45 and 5 GHz

Glucose concentration (mg/dL)	ε_r at 2.45 GHz	ε_r at 5 GHz
0	70	65
125	69	64
250	68.5	63.5
500	67	62.5

The finger phantom is simulated in an HFSS environment using layers of dielectric materials of various values. As mentioned in Table 1, the dielectric values at 2.45 GHz are considered for a healthy human finger. However, as the glucose concentration changes in the human blood, the dielectric values are also to be modified. The change of dielectric constant values in the finger phantom for different values of glucose concentration from 0 to 500 mg/dL is given in Table 2. As given in Figure 3, the finger phantom consists of different layers like skin, muscle, blood, fat, *etc.*, and each layer has its own dielectric constant value. When the glucose concentration in the blood changes, obviously, its dielectric value changes owing to the variations in the blood properties. The finger phantom is placed on top of the patch antenna, as shown in Figure 3(a), and for different values of glucose concentrations from 0 to 500 mg/dL, the S_{11} parameters are obtained, as shown in Figure 3(b). However, no shift in the frequency is observed. In the second case, the finger phantom is placed over the top of the antenna over the slots, as shown in Figure 4, and the corresponding shifts are observed in Figure 4(b). In this case, slight shifts in the frequencies are observed due to the variation of the field near the slot. Hence, an increasing or decreasing frequency shift is observed in the entire variation of glucose from 0 to 500 mg/dL. However, the obtained frequency shifts are not suitable for evaluating glucose concentration in the blood. Hence, the basic rectangular patch is not suitable for measuring glucose concentrations in the blood. Hence, in the following section, a new antenna giving considerable shifts in the frequency is described.

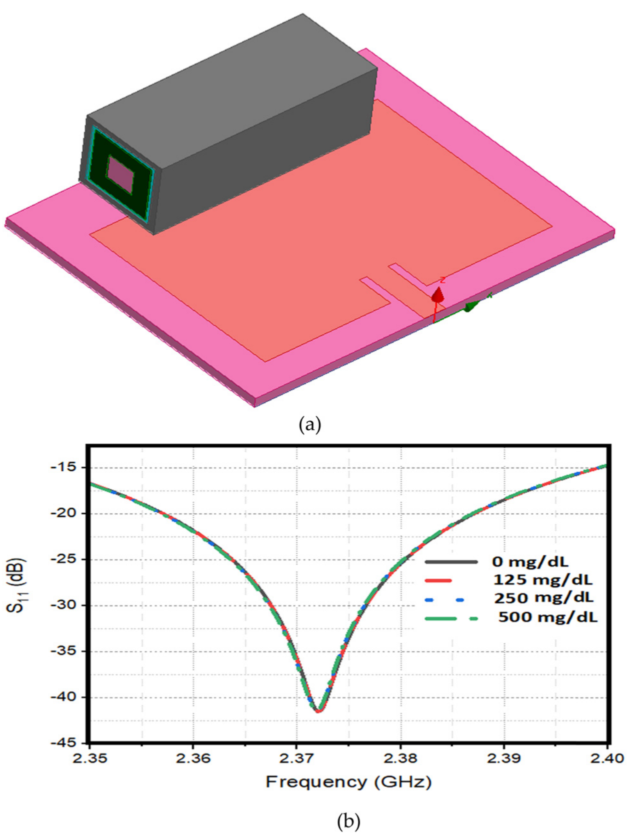
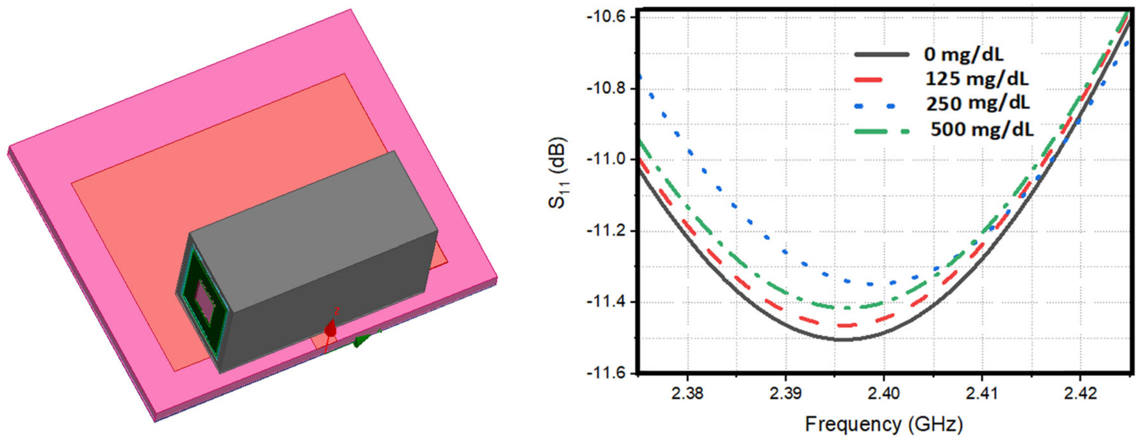


Figure 3: Finger phantom placed (a) on top of the antenna and (b) S_{11} parameters.

2.3 Slotted microwave sensor

As mentioned in the earlier subsection, the basic patch-type antenna is not suitable for glucose level measurements in the blood as no considerable shift in the frequency is observed due to less variation of the electric field at most of the antenna structure except at the slit. However, more variation of the electric field on the antenna is required for glucose level measurements. This owing to the greater variation of fringing fields on the antenna results in considerable change of the dielectric constant of the antenna, which in turn gives considerable frequency shift when the finger phantom is placed near the antenna. Hence, the basic patch antenna is modified by incorporating slots to get more variation in the electric field, as shown in Figure 5. The E-field distribution is shown in Figure 5(b), from which a good variation is observed near the slots, and this variation of the current distribution is desired for glucose monitoring, as discussed in the following sections. Various antenna dimensions are taken as W = 30 mm, W_1 = 14 mm, W_2 = 12.5 mm, W_3 = 3 mm, W_S = 1 mm, L_1 = 15.5 mm, and L_S = 1 mm. Two rectangular slots are employed on the antenna to increase electrical length, which causes the resonant frequency to shift towards the left [26,27]. This phenomenon is used to reduce the patch antenna dimensions to 2.45 GHz. Figure 6 describes the view of the finger phantom placed over the top of the antenna. Figure 6(b) gives the cross-section E-field variation when the finger phantom is placed over the antenna sensor. This figure clearly depicts a clear variation in the electric field owing to the placement of the phantom on the sensor. This is due to the systematic design of the slots over the antenna,



(a) (b)

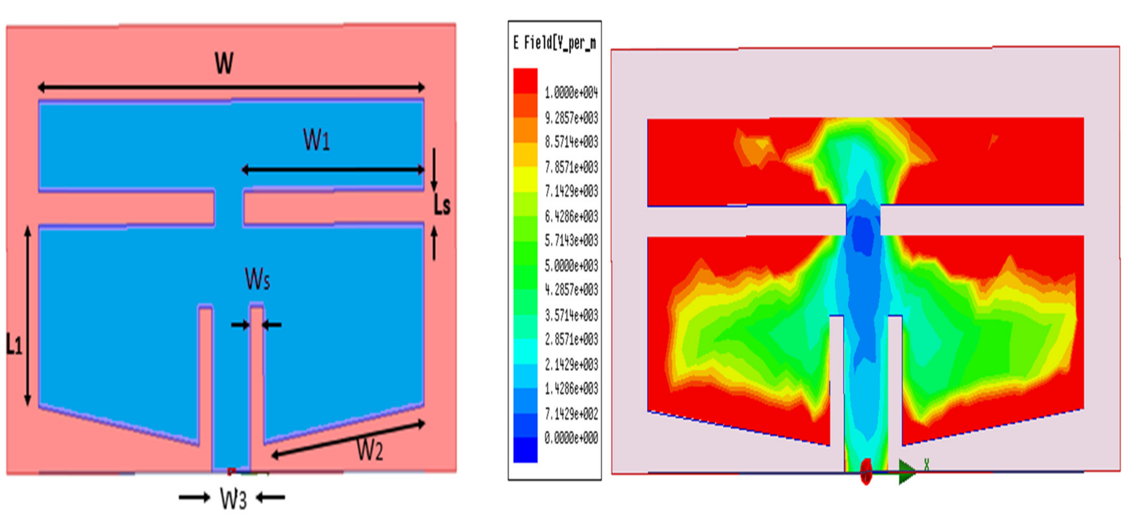
Figure 4: Finger phantom: (a) isometric view and (b) S_{11} parameters.

resulting in more field variation and thus making the sensor suitable for glucose monitoring. The presence of slots gives more variation of the electric field, thus causing variation in dielectric values, and hence, better frequency shift values can be obtained.

The S_{11} parameters and their variation for different glucose concentrations are shown in Figure 7(a and b), respectively. This slotted structure also resonates at the same frequency as that of a basic patch antenna, *i.e.* at 2.45 GHz. However, when the finger phantom is placed over the top of the antenna, as shown in Figure 6, the resonant frequency dominates at 5 GHz with good reflection coefficient values, as shown in Figure 7(b). Hence, this particular frequency is considered to study the frequency shifts w.r.t. variations in glucose concentrations. A small change in frequency shift is observed with glucose concentration variation, as shown in Figure 7(b). This shift resulted in the variation of electric field on the antenna structure, as mentioned earlier. However, this frequency shift is not sufficient to measure glucose concentrations in the blood as much shift is not obtained, and hence this slotted sensor is further modified, resulting in an arrow-shaped microwave sensor, which is discussed in the following sub-section.

2.4 Slotted arrow-shaped microwave sensor

Since the slotted microwave sensor mentioned in the previous sub-section does not give much frequency shift, the



(a) (b)

Figure 5: Slotted microwave antenna: (a) geometry and (b) E-field distribution at 2.45 GHz.

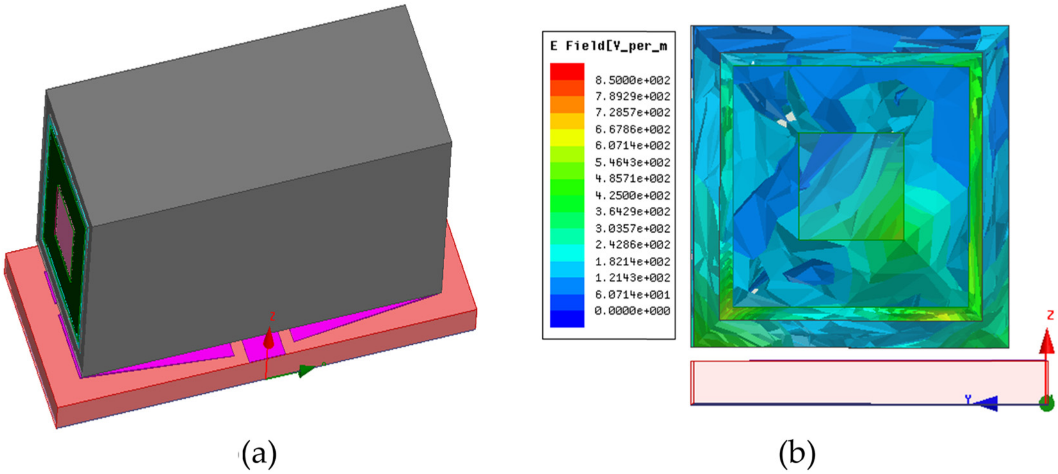


Figure 6: Phantom at the top of the antenna: (a) top view and (b) E-field distribution with finger phantom placed on top of the antenna.

antenna is further modified, resulting in the slotted arrow-shaped microwave sensor, as shown in Figure 8. Various dimensions of the proposed arrow-shaped sensor are given as W = 28.95 mm, W_a = 16.5 mm, W_b = 14 mm, W_3 = 3 mm, W_S = 1 mm, L_a = 4.75 mm, L_b = 1 mm, α = 75°, β = 60°. Overall substrate dimensions are maintained as 35 × 13.5 mm^2. Top and bottom views of the fabricated prototype are given in Figure 9(a and b), respectively. The microwave sensor is fabricated using a photo-lithographic fabrication process.

In Figure 10(a), the simulated S11-parameters are generated up to 5.5 GHz, where a second harmonic is observed at 5 GHz. Simulated and measured S_{11}-parameters of the slotted arrow-shaped sensor are given in Figure 10(b), where the first harmonic at 2.45 GHz is considered. The modifications of the design with slots and with the model of the finger appear to increase the resonance by about 5 GHz compared to the resonance at 2.45 GHz due to a better coupling with the feedline. A slight variation in the simulated and measured values is observed owing to the fabrication tolerances. The working of the proposed slotted arrow-shaped microwave sensor can be understood by considering the electric field distribution, as shown in Figure 11. As discussed earlier, the proposed antenna should have a considerable amount of field distribution over the entire surface of the antenna such that when the finger phantom is placed over it, the resonant frequencies of the antenna are affected. The reason is, as the phantom is placed over the sensor, its fringing fields are affected, thus affecting the dielectric value of the medium surrounding it. This in turn changes the resonant frequency of the antenna,

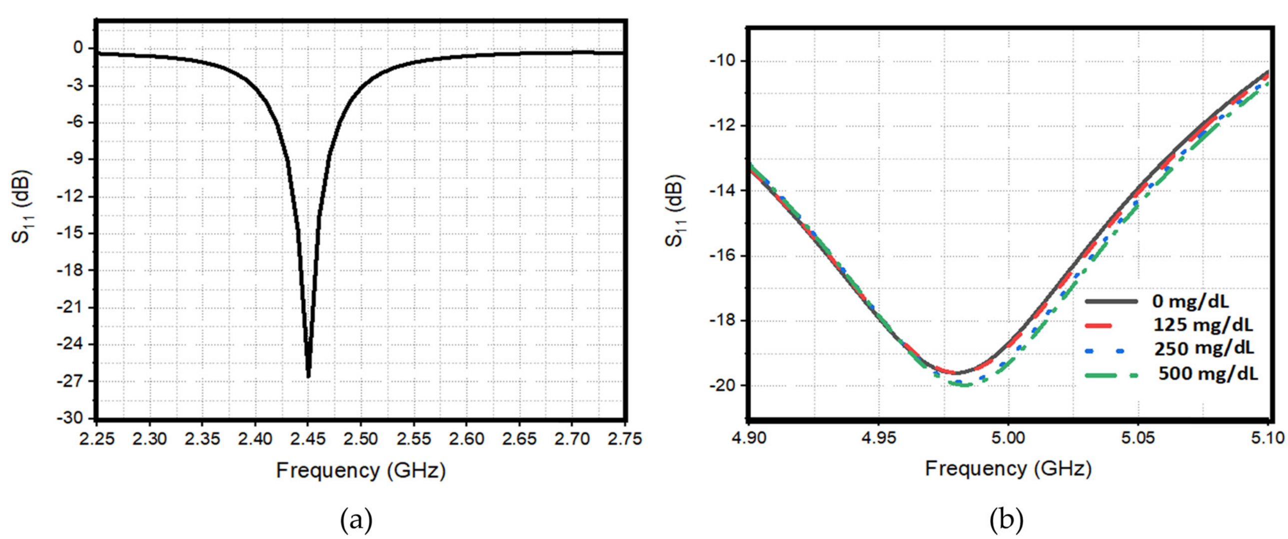


Figure 7: S_{11}-parameter: (a) slotted sensor without phantom and (b) variation with glucose concentration.

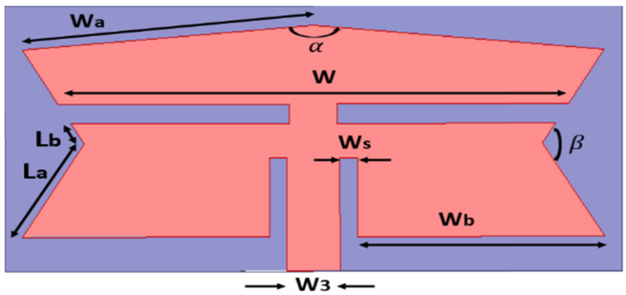


Figure 8: Proposed slotted arrow-shaped microwave antenna sensor.

and these changes are mapped to the changes of glucose concentration. As discussed earlier, this property is very much required to measure glucose level concentration in the blood. In order to obtain S-parameters and radiation patterns, vector network analyzer with model name Agilent N5247A:A.09.90.02 is used.

3 Experiment on proposed antenna's performance for various finger positions

In this section, the finger phantom is placed at various positions like bottom and top of the proposed antenna by varying glucose concentrations, and the resulting frequency shifts are observed. The detailed analysis is discussed as follows.

3.1 Finger phantom at the bottom of the antenna

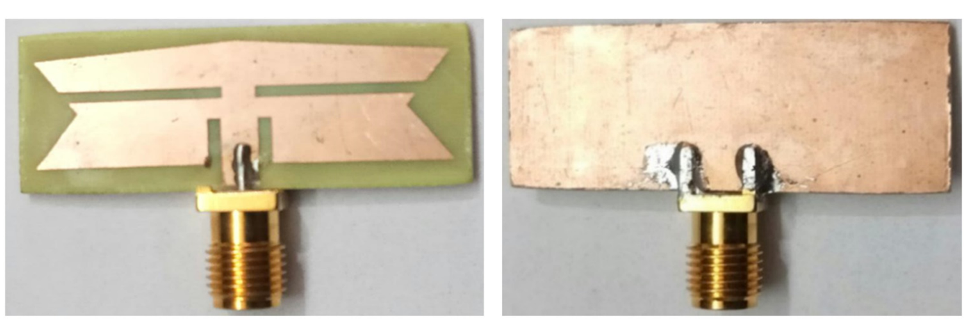
The human finger phantom discussed in the earlier sub-sections is placed at the bottom of the antenna at a spacing of 0.5 and 1.5 mm away from the feed point of the antenna, as shown in Figure 12. The cross-section of the E-field distribution on the phantom is given in Figure 12(c), from which it is observed that a considerable amount of E-field variation is observed throughout the phantom. For various levels of glucose concentration, *i.e.* from 0 to 500 mg/dL, the resultant S_{11} parameters are plotted as given in Figure 13. The graph indicates no variation in the frequency shifts, which is obvious as there is no field variation on the ground plane. However, this case is not helpful in evaluating glucose concentration as the shift is less. The next case of keeping a phantom on the top of the antenna is studied in the next sub-section.

3.2 Finger phantom at the top of the antenna

Initially, the finger phantom is placed at the top of the radiating element at a height of 0 mm and at 0 mm separation from the input port, as shown in Figure 14(a and b). For various levels of glucose concentration, *i.e.* from 0 to 500 mg/dL, the resultant S_{11} parameters are plotted as given in Figure 14(b). From the obtained graph, much frequency shift is not observed w.r.t. the glucose concentration variation and hence this case is not considered.

Another case of keeping finger phantom at the top of the sensor at a height of 0 mm and at a distance of 1.5 mm from the input port is considered as shown in Figure 15(a) and the resultant S_{11} parameters are given in Figure 15(b). From the S parameters, it is observed that no frequency shift is observed as the phantom and radiating patch are in direct contact. Hence, this case is also not useful in determining glucose concentration in the blood samples.

After performing exhaustive simulations by keeping the finger phantom at different locations on the antenna,



(a) (b)

Figure 9: Fabricated prototype: (a) top view and (b) bottom view.

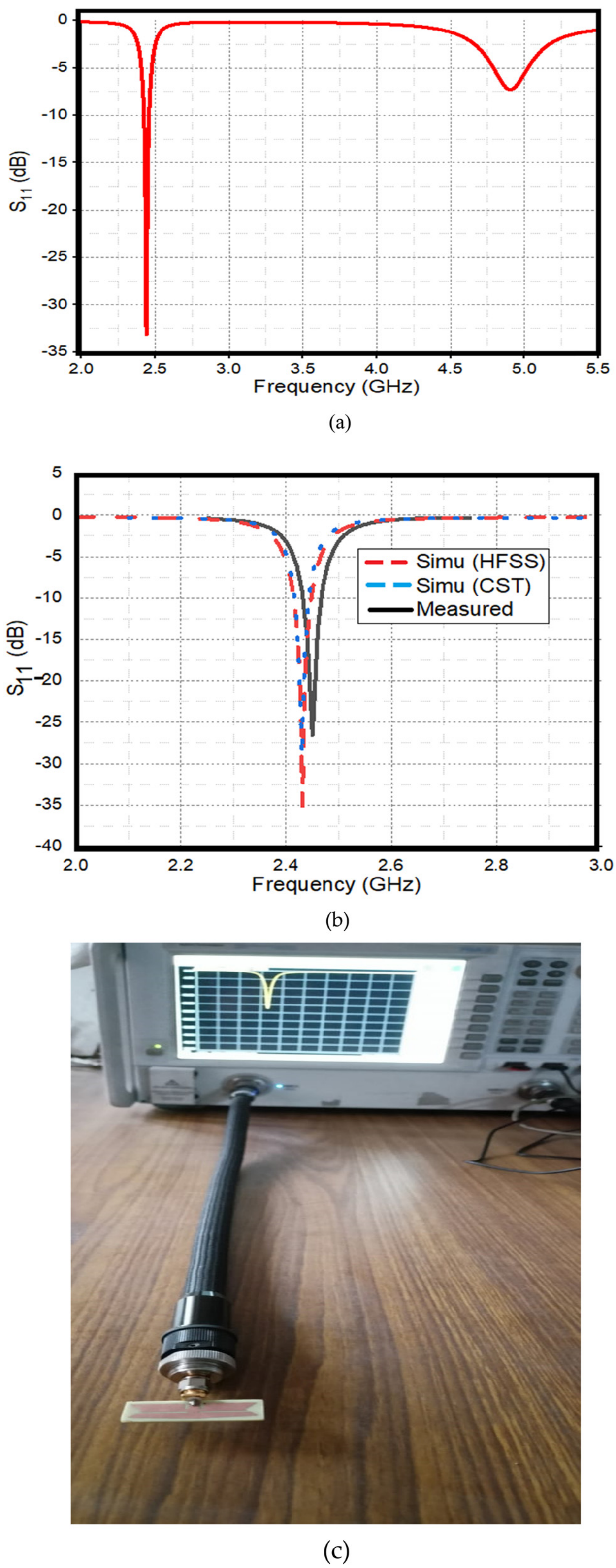


Figure 10: (a) Simulated S_{11}-parameters of the slotted arrow-shaped sensor, (b) comparison with HFSS and measured results, and (c) measurement setup.

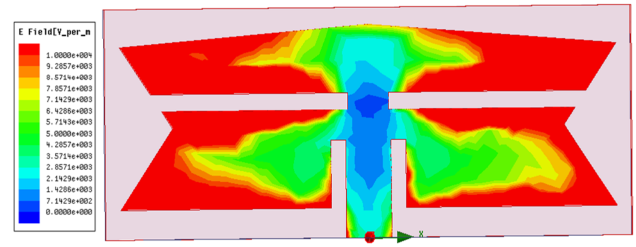


Figure 11: Electric field variation of the slotted arrow-shaped sensor at 2.45 GHz.

considerable frequency shifts with change in glucose concentration are finally observed when the finger phantom is at the top of the antenna at a height of 0.5 and 1.5 mm away from the antenna excitation, as shown in Figure 16. The proposed sensor is suitable for real-time calculations of the glucose variations in the blood samples as its dimensions are compatible with the real human finger, as shown in Figure 16(b). From Figure 16(b), it is observed that the size of the proposed antenna is compatible with real human finger. This would enable us to claim that the proposed sensor can be used in the real-time applications for the blood glucose level measurements. Figure 16(c) gives the cross-section E-field variation with the finger phantom placed on the antenna, from which maximum variation of E-field compared to all the previous cases is observed when the finger phantom is placed above the antenna at a height of 0.5 and 1.5 mm away from the antenna excitation.

For various levels of glucose concentration, *i.e.* from 0 to 500 mg/dL, the resultant S_{11} parameters are plotted as given in Figure 17(a). From Figure 17(a), it is observed that a clear and measurable frequency shift is observed by varying the glucose concentration levels. The obtained shifts with different glucose levels are given in Table 3, from which it is observed that good frequency shifts are obtained with changes in the glucose concentrations. When the glucose concentration is varied from 0 to 75 mg/dL, a frequency shift of 5 MHz is observed. When the concentration is varied from 75 to 125 mg/dL, a frequency shift of 4 MHz is observed. Similarly, the change of glucose concentration from 125 to 175 mg/dL gives a frequency shift of 2 MHz. From 175 to 250 mg/dL variation, a frequency shift of 3 GHz is obtained. From 250 to 375 mg/dL variation, a frequency shift of 1.75 GHz is obtained. Finally, when the concentration is in the range of 375–500 mg/dL, the obtained frequency shift is 1.25 GHz. As a clear shift in the frequency is observed for each case of glucose concentration variation, the proposed microwave sensor is a suitable device for predicting the glucose in the blood with minimum error. From the values given in Table 2, it is

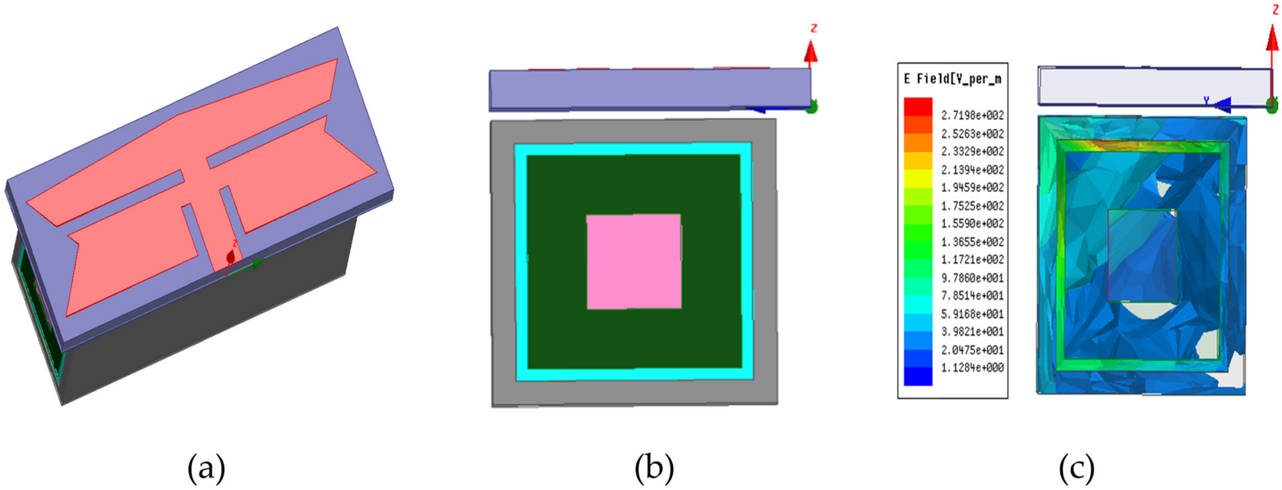


Figure 12: Phantom at the bottom of the antenna: (a) top view, (b) side view, and (c) E-field distribution with finger phantom placed.

observed that the proposed sensor gives good sensitive values at lower glucose concentration levels, *i.e.* in the range of 0–250 mg/dL.

For the case of 0 mg/dL, S_{11} parameters are measured by keeping the finger of a normal person on the top of the antenna, as shown in Figure 16(b), and are closely matched with simulation values and the comparison of both simulated and measured values are given in Figure 17(b). In addition to the frequency shift values, the other important parameters to be studied in Table 2 are sensitivity values. Also, good sensitivity values are obtained using the proposed microwave sensor, and a maximum sensitivity of 8.0 MHz/mg/mL is obtained as the glucose concentration changes from 75 to 125 mg/dL, as given in Figure 17(c). Also, the variation of resonant frequency w.r.t.

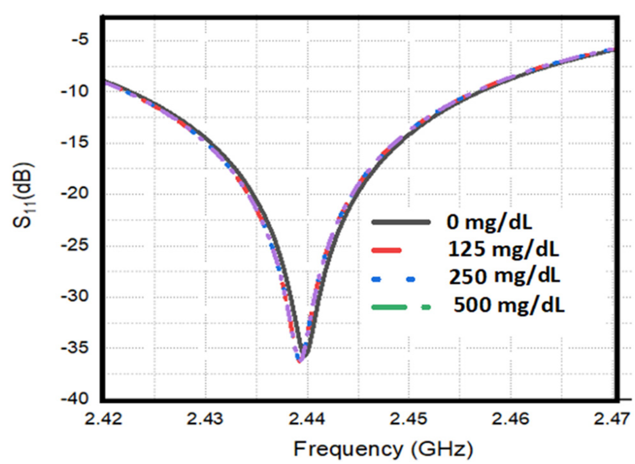


Figure 13: S_{11}-parameters variation with glucose concentration.

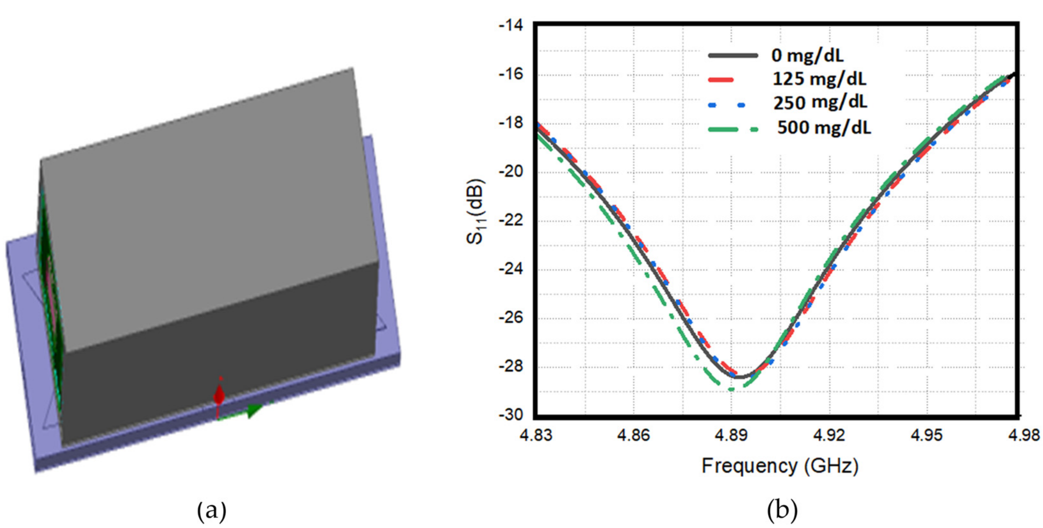
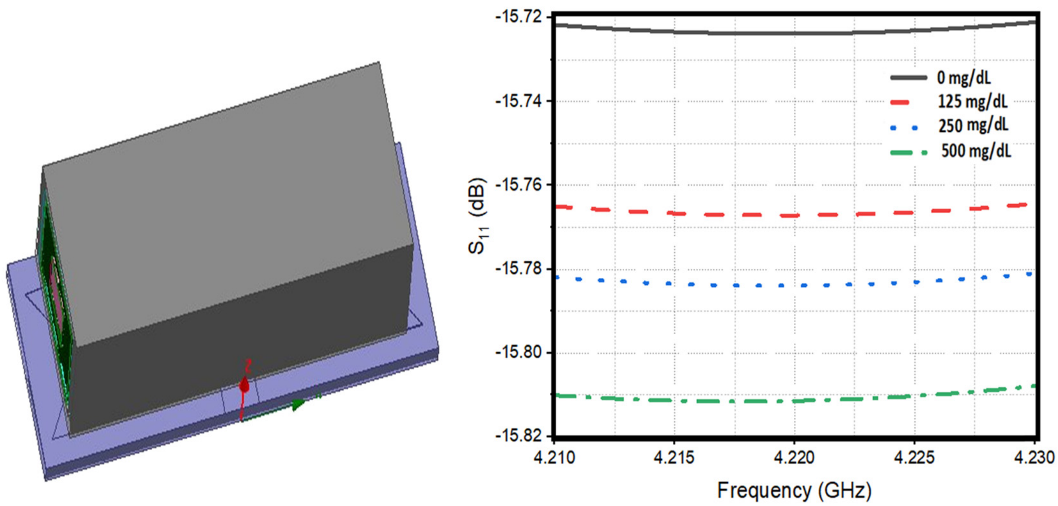
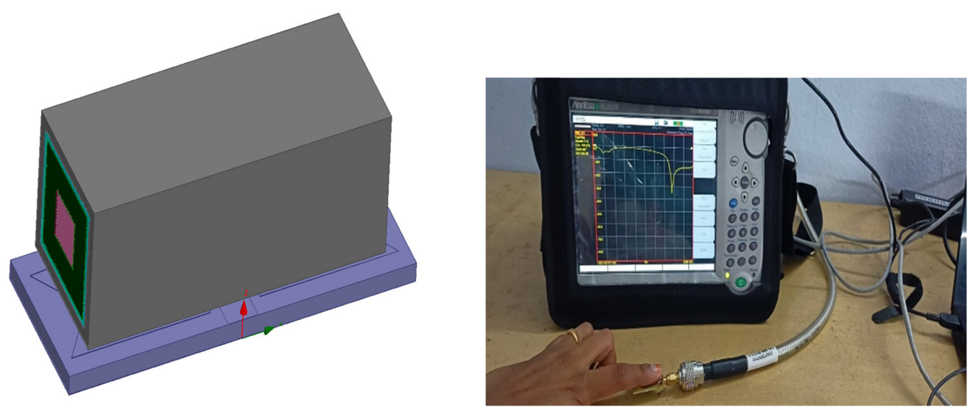


Figure 14: Phantom at the top of the antenna at 0 mm height and at 0 mm distance from input port: (a) top view and (b) S_{11} parameters.

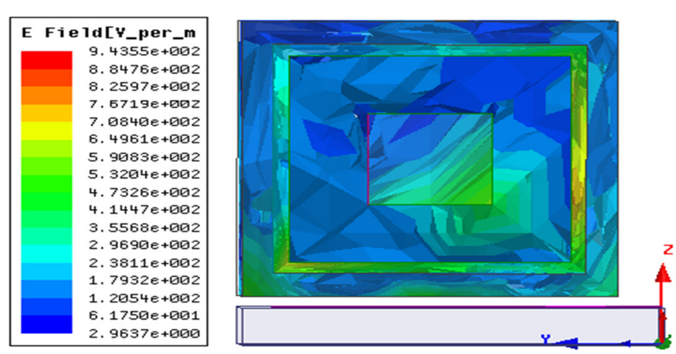


(a) (b)

Figure 15: Phantom at the top of the antenna at 0 mm height and at 1.5 mm distance from the input port of antenna: (a) side view and (b) S_{11} parameters.



(a) (b)



(c)

Figure 16: Phantom at the top of the antenna at 0.5 mm height and 1.5 mm distance from the input port of antenna: (a) top view, (b) at measurement, and (c) E-field distribution with finger phantom placed.

frequency is given in Figure 17(d). The sensitivity plots are obtained using the least-square error method, and the curve fitting is done by considering different ranges of glucose concentrations, and the plots are given in Figure 18. Figure 18(a) gives the sensitivity plot by considering glucose concentration in the range of 75–350 mg/dL, and the sensitivity is observed to be 3.5222 MHz/mg/mL, which is obtained from the slope of the curve. Similarly, Figure 18(b) gives the sensitivity value of 3.2881 MHz/mg/mL, which is plotted by considering glucose concentration in the range 125–300 mg/dL.

In order to validate, whether the square-shaped finger phantom chosen in the present experiment is apt or not, two more finger phantom shapes, *viz*. cylindrical and ellipsoid, are considered, as shown in Figure 19, and the frequency shifts are generated in Figure 20. From the plotted graphs, it is observed that either cylindrical or elliptical phantoms do not give satisfactory frequency shifts, and hence, the square-shaped finger phantom chosen in the experiment is the apt choice for glucose monitoring in the blood. The details are given in Table 4, from which it is observed that the better frequency shifts are obtained

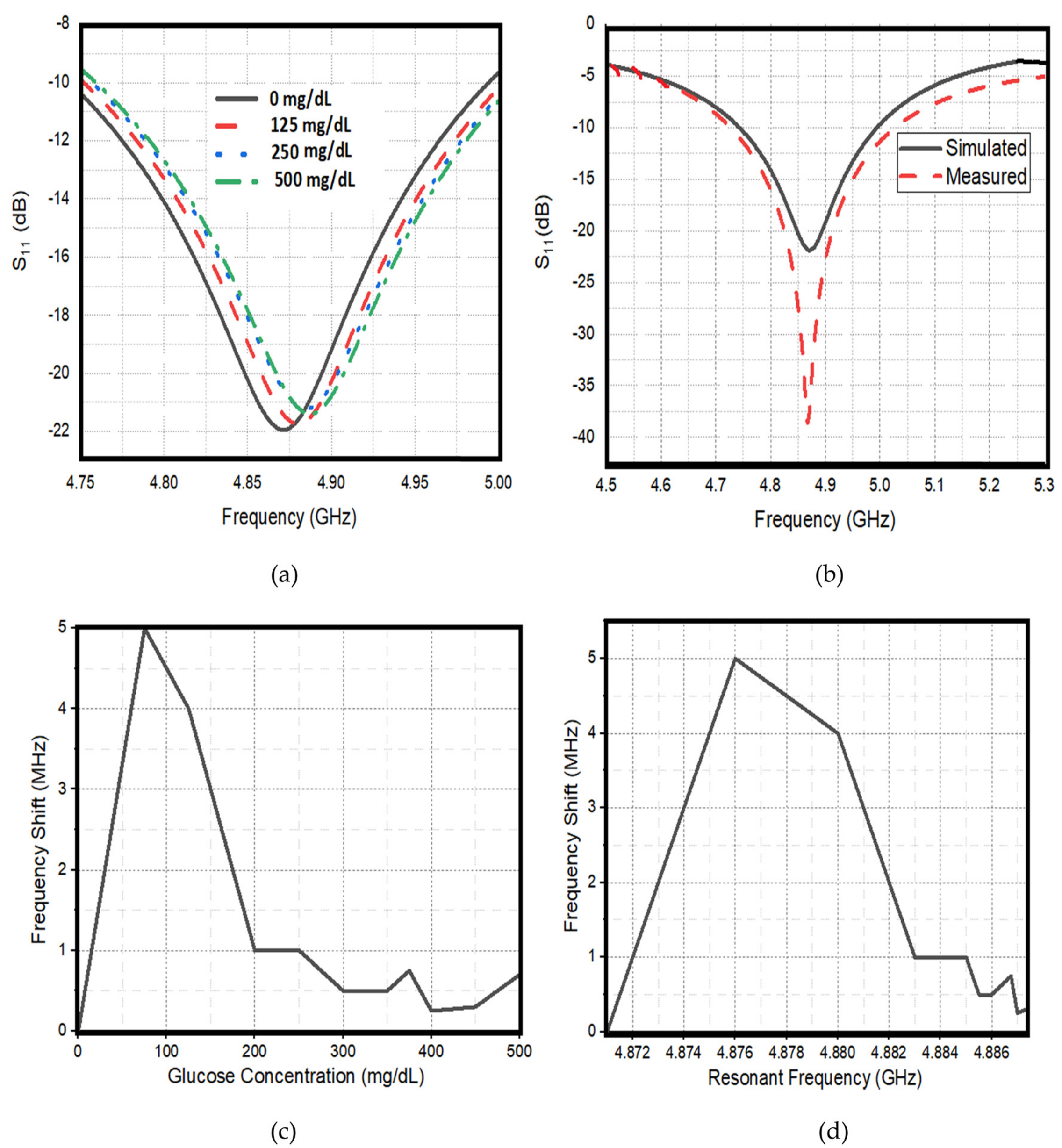


Figure 17: (a) S_{11}-parameter variation with glucose concentration, (b) comparison with measured value for 0 mg/dL case, (c) glucose concentration *vs* frequency shift, and (d) resonant frequency *vs* frequency shift.

Table 3: Summary of resonant frequencies obtained for different glucose concentrations

Glucose concentration (mg/dL)	Resonant frequency (GHz)	Bandwidth (GHz)	Q-factor	Frequency shift (MHz)	Sensitivity (MHz/(mg/mL))
—	2.45	0.035	70	—	—
0	4.8710	0.2571	18.946	—	—
75	4.8760	0.2585	18.8627	5	6.66
125	4.8800	0.2596	18.7981	4	8
175	4.8820	0.2594	18.8203	2	4
200	4.8830	0.2591	18.846	1	4
225	4.8840	0.2588	18.871	1	4
250	4.8850	0.2592	18.8464	1	4
300	4.8855	0.2598	18.804	0.5	1
350	4.8860	0.2602	18.776	0.5	1
375	4.88675	0.2612	18.7088	0.75	3
400	4.8870	0.2617	18.672	0.25	1
450	4.8873	0.2620	18.653	0.3	0.6
500	4.8880	0.2622	18.6422	0.7	1.4

using a square-shaped phantom, as the glucose changes from 0 to 500 mg/dL, whereas using cylindrical and ellipsoid phantoms, the total shifts obtained are too low making them unsuitable for glucose monitoring. Hence, for the present experiment, square-shaped phantom is the apt choice.

From the results discussed in this sub-section and previous sub-section, it is concluded that the better position to place the finger to measure the variation of glucose concentrations is on the top of the antenna at a height of 0.5 mm and a distance of 1.5 mm from the input port of antenna element. This is because a clear frequency shift is observed when the finger of a healthy person or a glucose concentration varying finger is placed above the antenna.

3.3 Two antenna models for glucose monitoring

From the analysis presented in the previous sub-section, it is concluded that better frequency shifts are obtained when the finger phantom is placed over the top of the

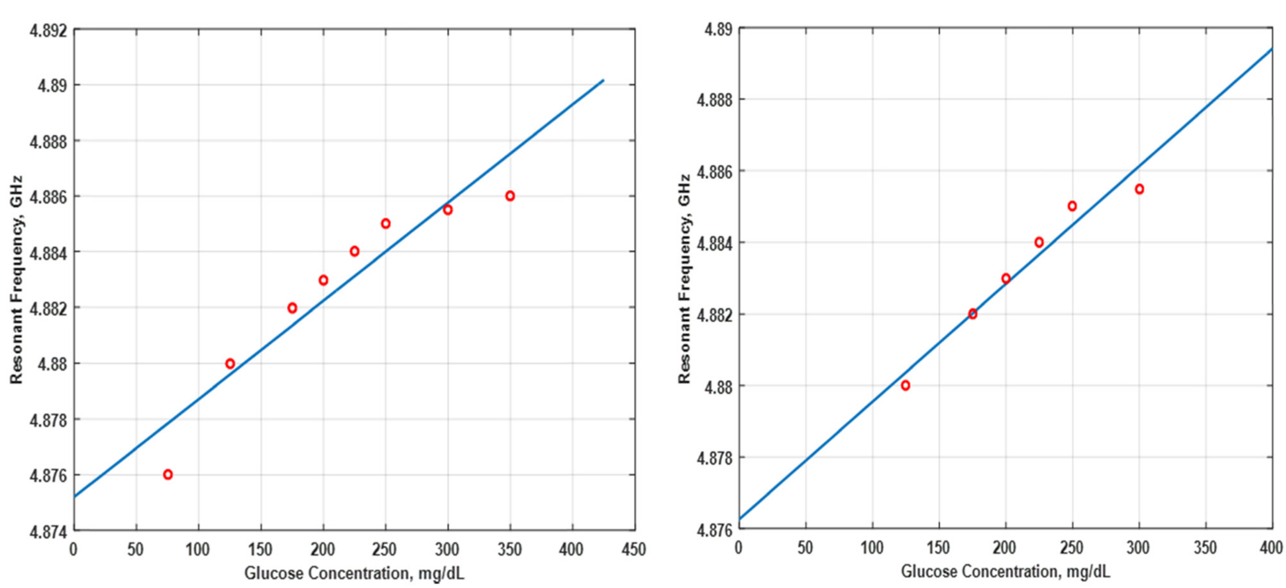


Figure 18: Sensitivity plots obtained using the least-square error method for varying glucose concentration from (a) 75 to 350 mg/dL and (b) 125 to 300 mg/dL.

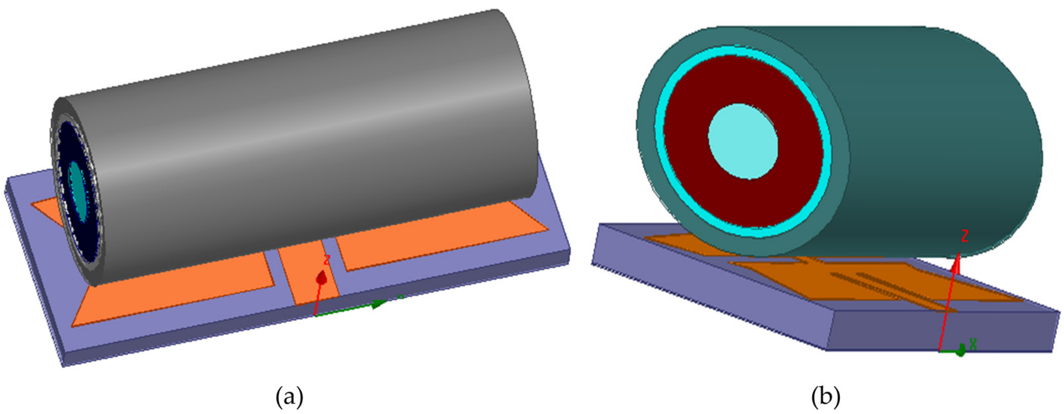


Figure 19: Various other shapes of finger phantom: (a) cylindrical finger phantom and (b) ellipsoid finger phantom.

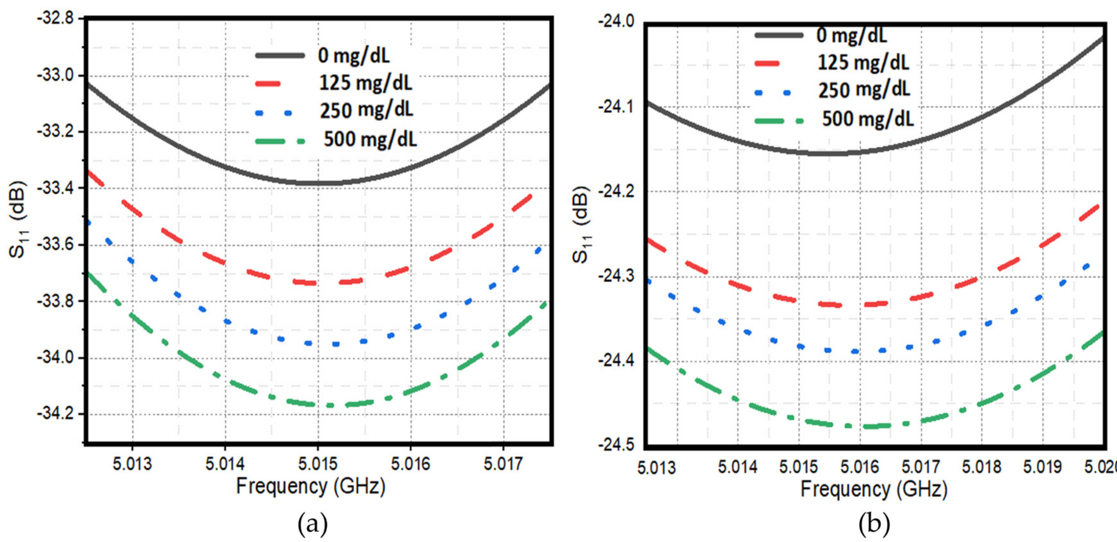


Figure 20: Frequency shifts obtained using: (a) cylindrical finger phantom and (b) ellipsoid finger phantom.

Table 4: Comparison of frequency shifts with various types of finger phantoms

Glucose concentration (mg/dL)	Frequency shift – cylindrical phantom (MHz)	Frequency shift – ellipsoid phantom (MHz)	Frequency shift – square-shaped phantom (MHz)
0	—	—	—
125	0	0.1	9
250	0.1	0.1	5
500	0.1	0.3	3

antenna at a height of 0.5 mm and a distance of 1.5 mm from the input port of the antenna element. In the present sub-section, for the first time, a two-antenna model is presented for glucose level monitoring in blood samples. The finger phantom is placed between the two antennas, as shown in Figure 21, and two important parameters, *viz*. group delay and isolation, are evaluated for different glucose concentrations.

In Figure 22(a), the variation in group delays with respect to frequencies is shown for different glucose concentrations, *viz*. 0, 125, 250, and 500 mg/dL. From the plot, it is observed that group delay is decreasing when the

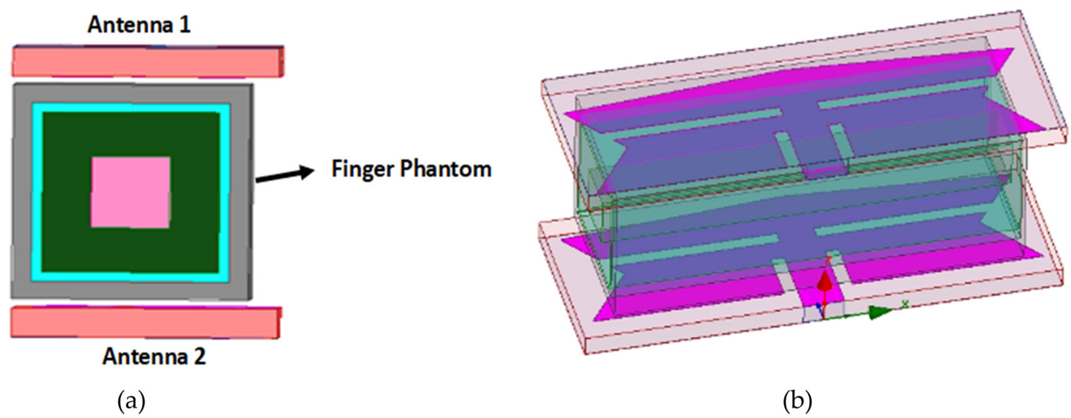


Figure 21: Two antenna models: (a) side view and (b) transparent view.

glucose concentration increases from 0 to 500 mg/dL. This is due to the fact that when the glucose concentration increases, a dielectric constant of the finger phantom decreases. The dielectric constant consists of real and imaginary parts, and the rate of decrease in the imaginary part is higher. Hence, the slope of the curve decreases as the concentration increases. The group delay is the derivative of the angle (function of frequency), and thus, the group delay decreases with increasing glucose concentration [3]. Similarly, isolation between the two antennas for different glucose concentrations is presented in Figure 22(b). A small decrement in isolation is observed with an increase in glucose concentration. This is due to the fact that the increase in glucose concentration decreases the dielectric constant of the phantom, which is placed in between the two antennas. The lesser dielectric constant results in more surface current, giving rise to lesser coupling. However, in the present case, a small change in the isolation is observed for different glucose concentrations.

The performance of the proposed microwave sensor is compared with some existing sensors in the literature that are used for glucose level monitoring and are given in Table 5. The work mentioned in the study of Turgul and Kale [31] developed a novel CPW sensor for measuring glucose concentration at 1.8 GHz operating frequency. However, the work mentions that the glucose concentrations are up to 16,000 mg/dL, which is practically not required. Also, the sensitivity values mentioned in the work are calculated from 100 to 500 mg/dL. In the study of Hasan *et al.* [32], a novel dielectric resonator antenna for evaluating glucose concentrations at 4.7 GHz has been presented, which also carries the calculations up

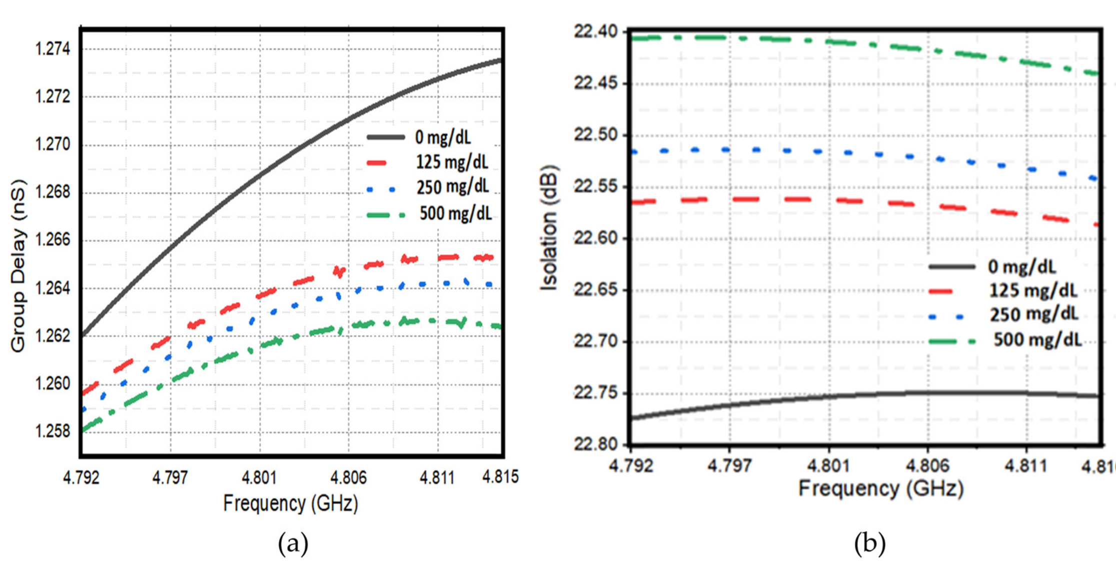


Figure 22: Glucose concentration variation w.r.t. (a) group delay and (b) isolation.

Table 5: Performance comparison of proposed work with literature

Ref.	Technology	Operating frequency (GHz)	Sensitivity	Measuring sample
[31]	Planar resonator	3.25	1.4 MHz/mg/mL	100–500 (mg/dL) (glucose variation in blood sample)
[32]	Non-invasive finger placed on dielectric resonator	4.7	0.281 MHz/mg/mL	0–16,000 (mg/dL) (glucose variation in blood sample)
[33]	Microstrip antenna sensor	2.5 to 18	—	0–80% of solution (detection of salt and sugar in water)
[34]	Non-invasive wearable split ring resonator	1.5	3.287 kHz per mM	4.4–7.6 mM/L (glucose variation in microfluidic sample)
[35]	Interdigitated capacitor (IDC) resonator-etched (CPW)	2.46	2 MHz/mg/mL	0–80 mg/ml (glucose concentration in glycerol)
[36]	Patch antenna sensor	2.378	2–8 MHz/80–160 µL	Detection of ice from 80 to 160 µL
[37]	Two-facing microstrip patch antennas	60	—	Glucose concentration in blood up to 1.33 mmol/l
[38]	Patch antenna	5	0.1 MHz/mg/mL	Glucose concentration in blood from 0 to 250 mg/dL
[39]	Single port resonator	4.8	1.4 MHz/mg/mL	Glucose concentration in blood from 100 to 1000 mg/dL
This work	Arrow-shaped compact microwave sensor	2.45	17 MHz/mg/mL	Glucose concentration in blood from 0 to 500 mg/dL

to 16,000 mg/dL and getting a sensitivity value of 0.28 MHz/mg/mL. Islam *et al.* [33] presented the novel design of a microstrip sensor operating in the wideband of 2.5–18 GHz for measuring sugar and salt in solutions, which has the main limitation of practical reliability. Choi *et al.* [34] presented a novel split ring resonator for measuring glucose concentration, however, giving a sensitivity of 3.287 kHz per mM. Similarly, the design of flexible biomedical RF sensors for monitoring glucose concentration in glycerol, operating at 2.46 GHz is presented in the study of Tiwari *et al.* [35]. In the study of Kozak *et al.* [36], a patch antenna sensor operating at 2.378 GHz for the detection of frost and ice is developed. In the study of Saha *et al.* [37], a two-facing microstrip sensor for monitoring glucose concentration in blood is presented. This work uses transmission coefficients to evaluate the glucose concentration. In [38], a patch antenna operating at 5 GHz is presented for glucose monitoring in blood samples with a sensitivity of 0.1 MHz/mg/mL over a glucose concentration range of 0 to 250 mg/dL. In the study of Turgul and Kale [39], another single port resonator operating at 4.8 GHz, giving a sensitivity of 1.4 MHz/mg/mL, is presented. The proposed antenna sensor gives a maximum shift of 17 MHz with a sensitivity of 3.4 MHz/mg/mL, making the proposed antenna sensor a good choice for measuring the glucose level variation in blood samples.

4 Conclusion

A planar compact and highly sensitive arrow-shaped microwave antenna sensor is developed for measuring glucose level concentration in blood. A human finger phantom is modeled using different dielectric constants of the skin layer, and the phantom is placed at various positions around the antenna, and the corresponding frequency shifts are observed by changing the glucose concentration from 0 to 500 mg/dL. From the obtained results, it is observed that better frequency shifts are obtained if the finger is placed at the top of the radiating element at a height of 0.5 mm and at a distance of 1.5 mm from the input port. Also, a two-antenna model is presented for estimating glucose concentration by calculating time delay and isolation. Also, Q-factor and sensitivity are evaluated to understand the performance of the proposed sensor. The experiment on the human finger using an antenna-fabricated prototype also presents good correspondence with the simulation results. The developed microwave sensor is a good choice for monitoring glucose concentrations in the blood due to its compactness, high sensitivity, and affordable cost and hence can be implemented for real-time applications.

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