

Parametric Analysis of Blood Dielectric Properties Using a Printed Microwave Antenna Sensor for In-Vitro Glucose Detection

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Abstract – More and more people are suffering from diabetes mellitus, a condition that requires accurate, non-invasive, and cost-effective ways to monitor blood sugar levels. Painful and limiting, traditional finger-pricking procedures restrict the frequency of examinations. Using changes in blood's dielectric characteristics as a basis, this research details the design and development of a miniature printed microwave antenna sensor for in-vitro glucose detection. Utilised ANSYS HFSS for analysis after designing a 5.5 GHz ISM band concentric rectangular loop Microstrip antenna utilising an inexpensive FR-4 substrate. A multi-layer phantom model of the human fingertip was used to replicate realistic sensing settings. This model incorporates skin, fat, blood, and bone components. Changes in the dielectric characteristics of blood caused by fluctuations in glucose allow for changes in the resonance frequency of the reflection coefficient (S_{11}), which in turn allow for changes in the sensing. Additionally, by individually adjusting the relative permittivity, conductivity, and loss tangent of blood, a comprehensive parametric analysis was carried out. According to the findings, resonance frequency shifts are greatly impacted by relative permittivity, but signal loss is largely affected by conductivity and loss tangent, and frequency shifts are barely affected by any of these parameters. In comparison to earlier reported microwave glucose sensors, ours showed a large resonance shift of 2.05 GHz upon phantom introduction, suggesting excellent sensitivity. The suggested antenna sensor has enormous potential for use in future non-invasive glucose monitoring systems due to its small size, ease of fabrication, and enhanced sensitivity.

Keywords – Printed Antenna, Dielectric properties, Relative permittivity, Printed planar antenna, In-vitro sensing

I. INTRODUCTION

A chronic disease with rapid global expansion, diabetes is characterised by persistently high blood sugar levels.

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Checking glucose levels on a regular basis is important for good management since it helps to prevent complications in the future. The majority of people still prick their fingers, which is a painful and inconvenient approach to check someone several times. When faced with pain or practical concerns, scientists often seek for other solutions [1]. Many research have been conducted in recent years focussing on methods to test sugar that do not need breaking the skin [2]. When it comes to non-invasive body scanning procedures, radio waves and microwaves stand out. Detecting changes in electrical properties inside physiological fluids allows them to measure glucose levels, since these signals respond differently based on the blood sugar level [3].

A few designs using microwave antennas show shifts in frequency or signal strength when glucose levels change [4]. Made on affordable materials like FR-4, flat antennas take up little space. Their simple build helps in medical sensing tasks. What stands out is how well they adapt to body-related uses. Antenna configurations including planar Yagi-Uda structures, Microstrip patch antennas, and resonator-based designs have been investigated for glucose sensing in both in-vitro and in-vivo environments. Transmission-based sensing techniques operating at millimetre-wave frequencies have also shown promising results; however, they often involve complex system architectures and higher implementation costs. To enhance sensitivity, resonant structures such as split-ring resonators (SRRs) and complementary split-ring resonators (CSRRs) have been integrated with microwave sensors to confine electromagnetic fields near the sensing region [6]. On-body and near-field microwave resonators have further demonstrated improved figures of merit by detecting glucose-induced dielectric variations in interstitial fluids and blood-mimicking solutions [7]. Despite these advancements, many reported designs primarily focus on glucose detection performance without systematically analysing the individual contribution of blood dielectric parameters. It has been experimentally demonstrated that glucose content affects many electrical characteristics of blood, including relative permittivity, conductivity, and loss tangent [8]. However, several studies indicate that resonance frequency shifts are predominantly governed by variations in relative permittivity, while conductivity and loss tangent mainly affect signal attenuation [9]. In order to examine how sensors, react to variations in glucose, it is crucial to isolate each variable. Researchers are now seeking printing-method devices that are compact, inexpensive, and capable of detecting minute glucose fluctuations in the absence of a cluttered setting.

Some have begun to employ a combination of antenna types, resonator materials, or mathematical models to improve performance and consistency, rather of relying on traditional kinds. The specific electrical properties of blood and how they impact flat printed antennas designed for this purpose have been the subject of few in-depth investigations. For use in non-invasive glucose monitoring, scientists have developed a novel flat microwave antenna operating at 5.5 GHz. Researchers used a stacked finger-like arrangement to alter blood properties one by one, such as its resistance to electric fields, current conductivity, or energy loss, rather than modifying everything at once. Resistance to electric fields is the most important factor to consider while monitoring sugar levels, as each change had an effect on the signal's bouncing back and the location of the tuning point. Better designs for touch-free sensors may be guided by this method's emphasis on these interactions, which helps elucidate how microwaves can detect glucose without needles.

II. RELATED WORK

The feasibility of non-invasive glucose monitoring using microwaves for painless, real-time diagnosis has prompted much research into this field. Much study effort has been devoted to investigating the feasibility of using microwaves to test glucose levels instead of needles. These techniques detect changes in antenna signals caused by alterations in the mobility of bodily tissues. Researchers first experimented using flat antennas constructed on standard circuit boards, detecting frequency changes in test fluids that mimicked blood [10]. As sugar levels fluctuated throughout stacked finger models, a separate setup saw clear movement in readings using a pointed design tuned around 5.5 gigahertz [11]. Another approach used very high-frequency pulses (about 60 gigahertz) sent over the skin by tiny paired emitters to detect minute electrical variations associated with glucose levels in real time during testing [12]. However, these configurations often need meticulous tuning in addition to high-frequency equipment, which hinders their practical use. The introduction of small slot-fed and Microstrip patch antennas operating at 2.45 GHz helped to reduce complexity and make things lighter [13]. Their almost linear reaction to variations in sugar levels suggested they would be useful for low-cost detecting jobs. To further refine readings, researchers have also experimented with flat microwave probes coupled with pattern-finding mathematical algorithms; nevertheless, the effectiveness of these approaches is very shape- and material-dependent. Devices based on resonance structures are now gaining a lot of attention due to their superior performance. Due to the significant reaction they have to even minute changes in material, small rings concentrate energy around the testing site. This is why split-ring devices are so good at picking up on minute variations in liquids, such as water or blood sugar levels [14]. Studies have shown impressive results using sensors that operate at rates ranging from 1 to 6 billion cycles per second. Identical ring-shaped devices detect changes in sugar levels via changes in the timing or intensity of impulses when applied to the skin; however, they need more work to construct [15]. Some systems integrate into sensor setups for glucose monitoring

and employ ceramic blocks that vibrate with radio waves instead of metal elements [16]. By combining several kinds, a single gadget can detect glucose levels and transmit data wirelessly. The complex geometries of such combinations make mass manufacturing more difficult, regardless of whether they perform better or save space. Scientific investigations have shown that blood sugar levels influence a number of electrical properties, including permittivity, conductivity, and energy loss [17]. Changes in permittivity are the most important factor in determining resonance frequency shifts, while conduction ability and loss determine the rate of signal weakening. However, the majority of the published work focusses just on sugar detection, ignoring the need to thoroughly analyse each dielectric factor [18]. In order to make behaviour more transparent and ensure consistent findings, experts have recently proposed the necessity for smaller, less expensive printed microwave detectors supported by deeper analysis. There are several designs for antennas and resonators, but there haven't been many complete evaluations that relate the electrical properties of blood to printed flat sensors for lab-based sugar monitoring. In order to fill in the gaps, our research focusses on a sensor that uses a flat, printed microwave antenna. It takes individual material characteristics, such as blood's resistance to electric fields, current conductivity, and energy dissipation, and modifies them individually rather than combining them all at once [19]. The change shows what elements are the most important for detection. Here, the details become clearer on the fine-tuning of such antennas for microwave glucose level surveillance.

III. PROPOSED ANTENNA SENSOR DESIGN

A. Design of Concentric Rectangular Loop Microstrip Antenna

A tiny rectangle-shaped loop takes centre stage here, built using Microstrip tech over a flat board made of FR-4 material. This base resists electric fields moderately, rated at 4.4, standing just under one millimeter tall. Measuring thirty-two by fifty-two across, it stays slim down to the last fraction of thickness. Its small footprint fits neatly into medical tools where space matters most.. The radiating element consists of two perpendicular rectangular strips with an extended square junction to minimize discontinuity effects and enhance impedance matching. Both the patch and ground plane are fabricated using copper with conductivity of 5.8×10^7 S/m. The antenna geometry is optimized to resonate near the 5.5 GHz ISM band. The design and simulation are carried out using ANSYS HFSS, a finite-element-based electromagnetic solver with adaptive meshing. The antenna is surrounded by air as the dielectric medium during initial simulation. Layout of the proposed sensor is shown below in Fig. 1.

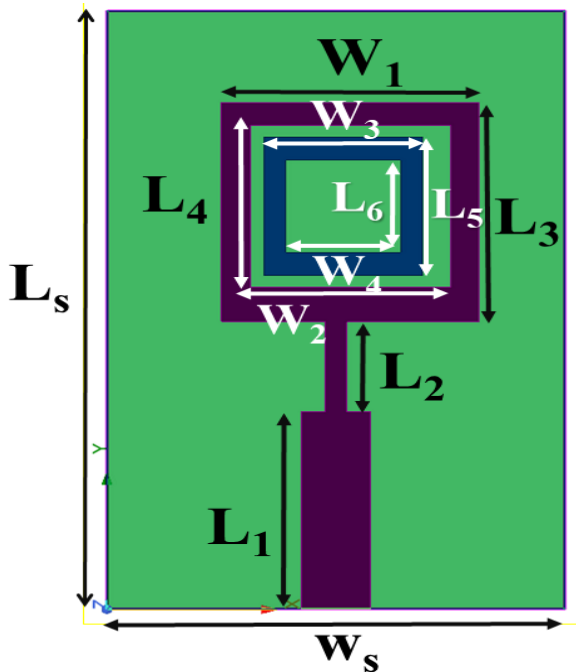


Fig. 1. Layout of the proposed printed microwave antenna sensor

The antenna consists of a concentric rectangular loop radiating structure placed on the top layer of the substrate and excited using a Microstrip feed line. Figure.2. illustrates the 3D geometry of the proposed printed planar microwave antenna sensor designed on an FR-4 substrate using HFSS tool.

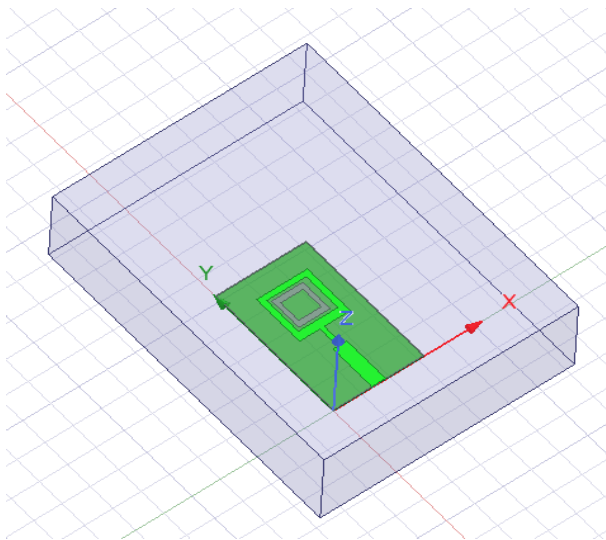


Fig. 2. HFSS 3D simulation model of the proposed printed microwave antenna sensor enclosed in an air box

The loop configuration is employed to enhance electric field confinement in the sensing region, thereby improving sensitivity to dielectric variations of the material under test. The antenna dimensions, including the outer loop length L_s , width W_s , inner loop dimensions, and feed line parameters, are optimized to achieve resonance around the 5.5 GHz ISM band. The proposed antenna element's different dimensions are presented in Table 1.

TABLE 1
GEOMETRICAL SPECIFICATIONS OF THE PROPOSED DESIGN

Parameters	Dimensions (mm)
L_s	52
L_1	17
L_2	7.8
L_3	19
L_4	14
L_5	12
L_6	8
W_s	32
W_1	18
W_2	14
W_3	11
W_4	8
H(thickness of Sub)	0.8

B. Phantom Model And Sensing Mechanism

To emulate realistic non-invasive glucose sensing conditions, a multilayer fingertip phantom model is employed. The phantom comprises four biological layers like skin, fat, blood, and bone, each characterized by frequency-dependent dielectric properties at 5.5 GHz. The phantom is placed as a superstrate at a distance of 3 mm above the antenna surface. When the antenna radiates electromagnetic waves, part of the energy penetrates the tissue layers and is reflected back to the antenna. Variations in blood glucose concentration alter the relative permittivity of blood, leading to measurable shifts in the antenna's resonance frequency.

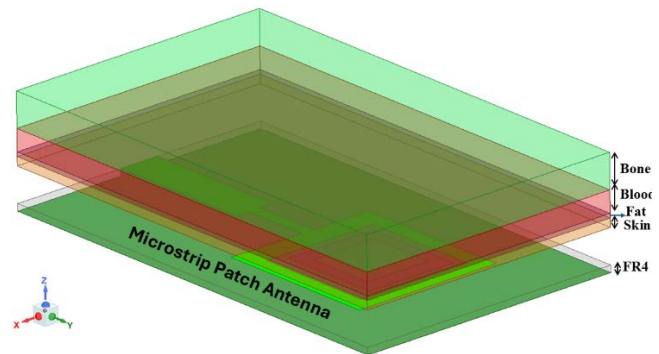


Fig. 3a. Front view of phantom model in HFSS

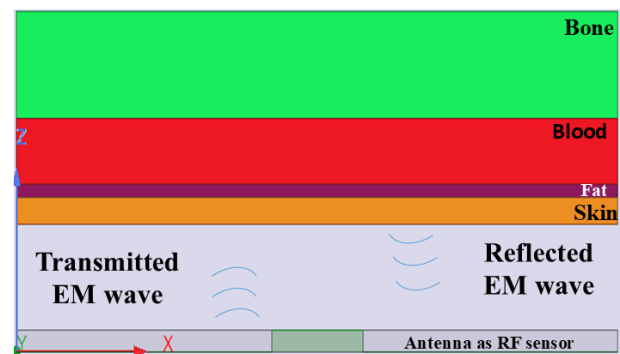


Fig. 3b. Back View of phantom model in HFSS

Among the electrical properties of blood, relative permittivity is found to have the dominant influence on resonance frequency, whereas conductivity and loss tangent

have comparatively minor effects. Figure.3a shows a schematic of a multilayer fingertip phantom positioned above the proposed sensor. The model includes layers representing skin, fat, blood, and bone, with glucose concentration in the blood considered higher than in other tissues. Figure.3b shows the front view of the simulation - antenna plus body-like material layered on top. Waves shoot out from the device, moving deep into fake skin made to act like real human layers. Some energy bounces after hitting inner levels, returning to where it started. That return signal strength shows up as S_{11} , measured in dB units. The antenna's optimal operating point, or peak tuning spot, changes in relation to that number. This motion is strongly related to changes in blood sugar levels that do not use needles. A fingertip is used as an extra outside slab during modelling to test this contactless notion. It lies just above the surface. The location of a finger alters the behaviour of signals in its vicinity, influencing characteristics such as tuning point, bounce-back level, resistance at entrance, and output intensity. The materials that make up the body alter the waves' performance only by being in close proximity to them.

TABLE 2
ELECTRICAL CHARACTERISTICS OF THE PHANTOM AT 5.5 GHZ

Human tissues layer	Dielectric constant (ϵ_r)	Dielectric loss tangent ($\tan\delta$)	Conductivity (σ), S/m	Thickness, (mm)
Fat	5	0.18	0.27	0.5
Skin	35	0.32	3.5	1
Blood	53	0.32	6	2.5
Bone	16	0.42	2	4

The thumb is modeled as a multilayer structure comprising skin up front, then fat, followed by blood vessels, finally bone deep inside each with distinct electrical properties. Each part handles electricity differently, especially when signals move through them. When the system runs at 5.5 gigahertz, how waves travel depends heavily on traits like resistance, energy loss, density, and layer depth. What those numbers actually are - values for insulation strength, signal fade, flow ease, and thickness shows up clearly in Table 2.

IV. RESULTS AND DISCUSSION

A. Simulation of Proposed Antenna Without Phantom

This section presents the findings from both modeling and measurement of the proposed antenna-based sensor. Fig. 4 depicts the fluctuation of the reflection coefficient ($|S_{11}|$) with frequency when the antenna is simulated in free space without a biological phantom. The sensor resonates at 3.45 GHz with a reflection coefficient of around -16 dB, showing good impedance matching at this frequency. Fig. 5 depicts the $|S_{11}|$ response of a human tissue phantom positioned 3 mm above the antenna surface.

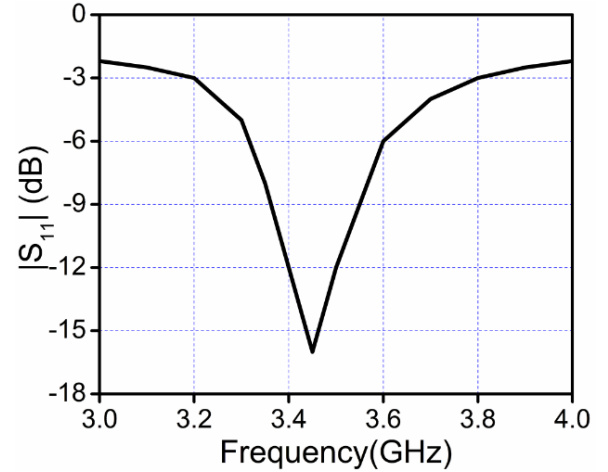


Fig. 4. Simulated results $|S_{11}|$ proposed antenna without phantom

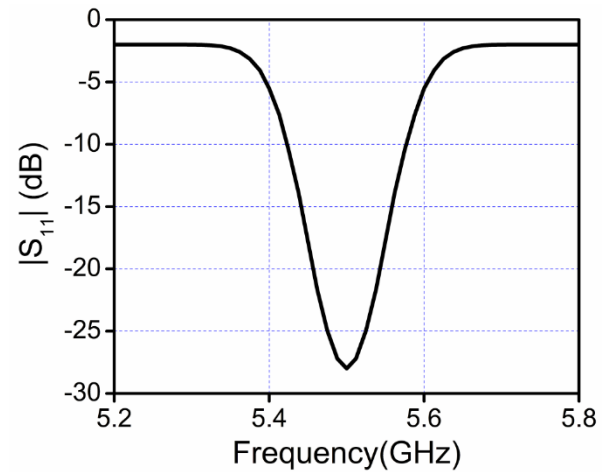


Fig. 5. Simulated results of $|S_{11}|$ when phantom placed 3mm above antenna.

The interaction as demonstrated in the Fig.5, the interaction of transmitted electromagnetic waves with the multilayer tissue structure results in a considerable shift in the resonance frequency. This frequency shift is caused by changes in the effective dielectric environment created by biological tissues and is directly proportional to fluctuations in blood glucose content. The reported resonance frequency shift is 2.05 GHz, ranging from 3.45 GHz to 5.50 GHz, and the sensor has a gain of 27.19 db. This large shift verifies the proposed sensor's sensitivity to dielectric changes in human tissue, demonstrating its applicability for non-invasive blood glucose monitoring applications.

B. Parametric Analysis of Electrical Property Variations on Sensor Performance

To determine blood glucose levels, utilize the relative permittivity of blood as a reference measure. We did parametric analysis to produce the best possible results by adjusting the relative permittivity of blood from 53 to 68 with a step value of 5 as shown in Fig. 6. The figure shows that the sensor's operating frequency shifts to a lower return loss when the relative permittivity increases in a linear manner.

As blood conductivity rises, impedance matching gets better, as shown by the change in the reflection coefficient

($|S_{11}|$) in relation to conductivity. Figure 7 shows that the lossy dielectric loading on the printed microwave antenna sensor gets bigger when blood conductivity goes up to 11 S/m, which is linked to higher glucose levels. The increased conductive loss at the antenna input makes $|S_{11}|$ more negative because it reduces the reflected power. This makes it easier for the blood medium to absorb electromagnetic energy. If you look at changes in dielectric characteristics, you can find glucose in vitro. The trend suggests that the antenna sensor may also be able to find changes in conductivity. But too much conductivity can make electromagnetic fields too weak, which lowers radiation efficiency and limits sensing depth. So, even though the S_{11} response is very sensitive to changes in blood conductivity, it needs to be carefully calibrated to find the right balance between sensitivity and signal robustness in order to accurately measure glucose levels.

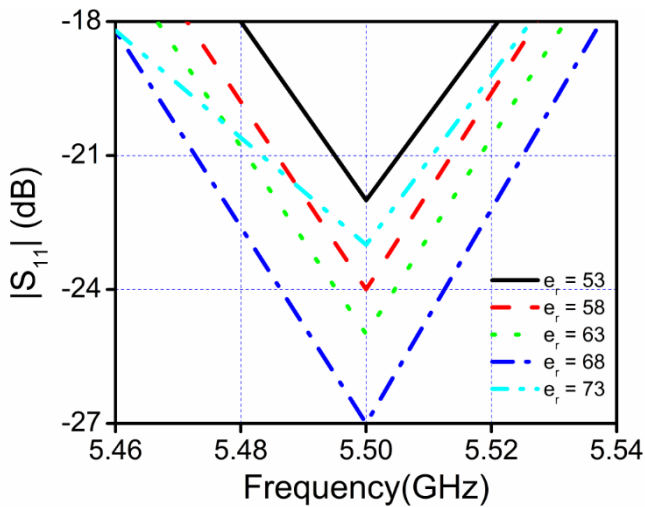


Fig. 6. Variation in reflection coefficient S_{11} for relative permittivity

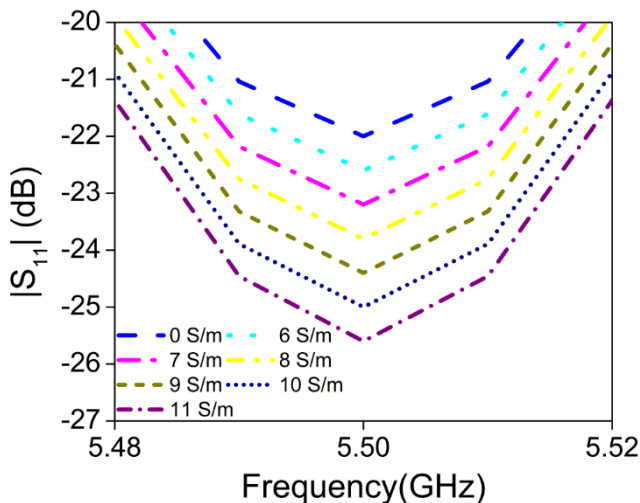


Fig. 7. Variation in reflection coefficient S_{11} for conductivity

Fig.8 depicts the variation of the reflection coefficient S_{11} for loss tangent values ranging from $\tan(\delta) = 0$ to 1.0. As the loss tangent increases, the resonance depth reduces significantly due to enhanced dielectric losses in the blood medium. Despite this variation, the resonance frequency

exhibits only a negligible shift, indicating minimal sensitivity of frequency displacement to loss tangent changes.

Parametric analysis is made at different values, the relative permittivity of blood moves between 53 and 68, tied to shifting glucose levels. As this property increases, resonance frequency slides upward in a straight-line pattern, showing clear response to glucose-linked dielectric behavior. While conductivity fluctuates, its effect on frequency remains minimal; similarly, changes in loss tangent barely alter the peak position. Instead, those two factors mainly reduce signal strength without nudging the frequency much. Across tests, only permittivity drives notable shifts - others fade into background noise. One standout result: a 2.05 GHz change emerges, exceeding performance seen in most prior microwave designs. Each material property was adjusted alone during testing, isolating their roles. Permittivity stands out as the key influencer, pulling the frequency along, whereas the rest dim the output slightly but leave tuning untouched. A clear link between resonance frequency and relative permittivity shows the design works well for consistent glucose detection. When compared with similar devices, this antenna stands out due to higher sensitivity, smaller dimensions, broader bandwidth, along with better signal strength - without complicating how it is made.

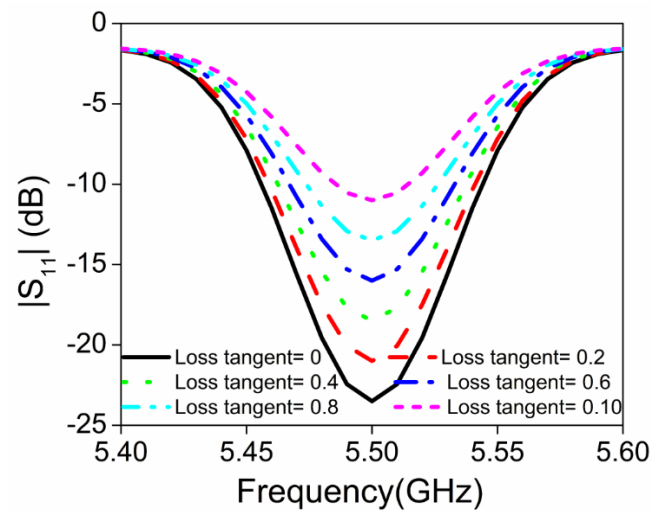


Fig. 8. Variation in S_{11} versus Loss Tangent

Table 3 presents a comparative analysis of the proposed antenna-based glucose sensor with existing microwave sensing techniques reported in the literature. The comparison highlights key parameters such as substrate material, sensor size, operating frequency, frequency shift, and sensing methodology. It is evident that the proposed sensor achieves a significantly larger frequency shift while maintaining a compact structure on a low-cost FR-4 substrate. This indicates improved sensitivity and suitability for non-invasive blood glucose sensing applications.

TABLE 3. COMPARISON OF THE PROPOSED SENSOR WITH ANOTHER EXISTING SENSOR FOR BLOOD GLUCOSE SENSING APPLICATIONS

Reference	Substrate	Dimension (mm ²)	Resonance Frequency	Frequency Shift	Technique Used
[1]	FR-4	30 × 40	5.5 GHz	26 MHz	S_{11}
[3]	FR-4	35 × 13.5	2.45 GHz	5 MHz	S_{11}
[6]	FR-4	66 × 20	2.5 GHz	3.5 kHz	S_{11}/S_{21}
[8]	FR-4	40 × 40	3.25/4.67 GHz	30MHz	S_{11}
[9]	FR-4	30 × 40	5.5 GHz	4 MHz	S_{11}
[10]	FR-4	50.66 × 60.31	2.4 GHz	7.5 MHz	S_{11}
[11]	FR-4	30 × 30	5.7 GHz	1.7 GHz	S_{21}
[12]	FR-4	32 × 22	3-17 GHz	30/240 MHz	S_{11}
[16]	FR-4	25 × 30	2.40/5.725GHz	0.1 G Hz	S_{11}
[17]	FR-4	51.3×51.3	2.4 GHz	1.2 G Hz	S_{11}
Proposed sensor	FR-4	32 × 52	5.5 GHz	2.05 GHz	S_{11}

V. CONCLUSION

This work has presented a compact printed planar microwave antenna sensor for in-vitro blood glucose by detecting shifts in electrical characteristics of blood. Cantered loops, shaped as rectangles, formed a Microstrip layout functioning at 5.5 GHz within an industrial-scientific-medical range, built upon affordable composite material used widely in circuit boards; evaluation occurred via layered finger-like structure models simulating practical contact-free measurement settings. The interaction between electric fields and blood components is affected by sugar levels, which causes signal behaviour to change at certain frequencies as shown in return loss patterns. Changes to the material's reaction allow for performance improvements despite unaltered dimensions. It seems that variations in permittivity, rather than conductive characteristics, are substantially related to frequency shifts. This model deviates more from the baseline under the same testing circumstances as previous versions. Typically, signal attenuation occurs with higher energies dissipated. Here, responsiveness is unaffected by a smaller physical footprint. Simple manufacturing without complicated changes is made possible by design layout. Increased operating range ensures consistent output regardless of the inputs. When exposed to the target medium, the amount of the shift increases to a noticeable degree. The main factor is the effect of dielectric properties on wave propagation. The

resistive components of the sample cause the resonant point to deviate as little as possible. Contactless glucose measurement has never been more practical, accurate, or inexpensive than with this printable microwave antenna sensor design. Fabrication of prototypes, experimental validation using a vector network analyser, and extension of the method towards non-invasive glucose monitoring devices that can monitor glucose levels in real-time will be the focus of future study.

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