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Design Of A Skin Patchable Electromagnetic Biosensor For Non-Invasive Glucose Monitoring

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Abstract

This paper introduces a novel skin-patchable electromagnetic biosensor designed for continuous, non-invasive monitoring of blood glucose levels. The proposed device leverages advanced complementary split-ring resonator (CSRR) technology in a honeycomb configuration to achieve high sensitivity and precision in glucose detection. Operating within the 2.4 GHz ISM band, the sensor is fabricated on a flexible polyimide substrate, enabling it to conform seamlessly to the skin's surface. The unique sensor design localizes intense electromagnetic fields in the sensing region, optimizing interaction with glucose samples and enhancing detection accuracy.Extensive simulations and experiments demonstrate the sensor's capacity to detect glucose levels within the physiological range of 70–180 mg/dL, yielding a sensitivity of 0.94 MHz/(mg/dL) through frequency shift analysis. To validate its functionality, the sensor's performance was assessed using a Vector Network Analyzer (VNA) and radar systems. The results highlight the sensor's reliability, low-cost fabrication, and potential for integration into wearable systems.This work represents a significant advancement in diabetes management, offering an accessible, pain-free, and real-time solution for blood glucose monitoring. Future efforts will focus on integrating artificial intelligence algorithms for enhanced signal interpretation and personalization, paving the way for a robust, commercially viable medical device.

Keywords: *Electromagnetic Biosensor, Non-Invasive Glucose Monitoring, Complementary Split-Ring Resonators (CSRR), ISM Band (2.4 GHz), Blood Glucose Level Detection, Skin-Patchable Device, Frequency Shift Analysis, Wearable Technology, Diabetes Management, Flexible Substrate*

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I. Introduction

Diabetes mellitus is a chronic metabolic disorder that poses significant health challenges worldwide. It is characterized by the body's inability to produce or effectively utilize insulin, resulting in elevated blood glucose levels. The International Diabetes Federation (IDF) estimates that over 500 million adults are currently living with diabetes, and this number is expected to rise dramatically in the coming decades. Among the various management strategies for diabetes, continuous glucose monitoring (CGM) plays a pivotal role in enabling patients to maintain glycemic control and prevent complications such as cardiovascular diseases, neuropathy, retinopathy, and nephropathy.

Traditional glucose monitoring methods, including finger-prick tests and minimally invasive CGM devices, have notable drawbacks, such as pain, inconvenience, high costs, and risks of infection. These factors often lead to poor patient compliance and irregular monitoring, increasing the likelihood of glycemic fluctuations. This necessitates the development of innovative, non-invasive solutions that are user-friendly, cost-effective, and capable of providing real-time, continuous glucose data.

This paper presents the design and development of a skin-patchable electromagnetic biosensor for non-invasive glucose monitoring. The proposed system employs Complementary Split-Ring Resonators (CSRRs), known for their ability to localize and amplify electromagnetic fields within a specific frequency range. The sensor is integrated into a flexible polyimide substrate, allowing it to conform to the skin's surface and measure glucose levels from interstitial fluids without piercing the skin. By operating within the 2.4 GHz ISM band, the sensor ensures optimal penetration depth and sensitivity, enabling accurate detection of blood glucose levels in the physiological range.

The innovative aspect of this biosensor lies in its honeycomb configuration of CSRRs, which enhances the interaction between electromagnetic fields and glucose molecules. This design significantly improves sensitivity and detection accuracy by inducing measurable frequency shifts in response to variations in glucose concentrations. Additionally, the sensor's compact size, low power consumption, and minimal health risks make it suitable for integration into wearable medical devices.

The potential applications of this device extend beyond diabetes management. The sensor's versatile design and robust detection capabilities open new avenues for non-invasive diagnostics in various biomedical domains, such as hydration monitoring, electrolyte imbalance detection, and continuous health monitoring for critically ill patients. This report details the sensor's design principles, fabrication process, experimental validation, and future prospects, demonstrating its promise as a transformative tool in healthcare technology.

II. Literature Review

In recent years, non-invasive glucose monitoring technologies have gained immense attention as alternatives to conventional invasive methods, which rely on blood sampling. These traditional approaches, such as finger-pricking and Continuous Glucose Monitoring (CGM) systems, though effective, involve discomfort, potential risks of infection, and high costs. As the prevalence of diabetes rises globally, the demand for painless, cost-effective, and user-friendly glucose monitoring solutions has driven research into non-invasive technologies, with electromagnetic sensing emerging as one of the most promising approaches.

Electromagnetic glucose sensors operate by detecting variations in the dielectric properties of tissues, which correlate with glucose concentration. Complementary Split-Ring Resonators (CSRRs) are particularly effective in this context due to their ability to confine and amplify electromagnetic fields. Villena Gonzales et al. (2019) emphasized that RF-based systems, operating in specific frequency bands like the ISM band, have demonstrated considerable potential in detecting physiological glucose levels non-invasively. These devices can be integrated into compact, wearable systems, offering real-time glucose monitoring without requiring invasive procedures.

Skin-patchable sensors represent a breakthrough in wearable technology for glucose monitoring. These devices employ flexible substrates such as polyimide, which conform to the skin and facilitate consistent sensor-tissue contact. Research by Heikenfeld et al. (2018) highlighted the utility of flexible materials in enhancing sensor comfort and adhesion, making them ideal for continuous use. Similarly, Abunahla et al. (2019) proposed incorporating metal-oxide-metal sensing structures to improve sensitivity at physiological glucose concentrations.

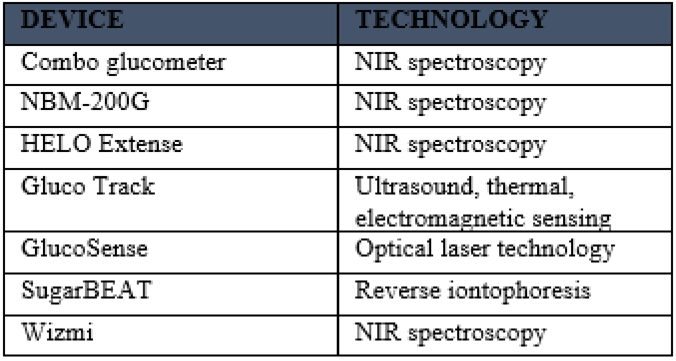
Non-invasive methods like optical and photoacoustic techniques have also been investigated. Optical spectroscopy, including Raman and near-infrared methods, can provide accurate glucose readings but faces challenges related to cost, device complexity, and sensitivity to environmental variables. By contrast, electromagnetic sensors are less affected by such factors and are more suitable for integration into portable and wearable systems. Adeel et al. (2020) compared these modalities and noted that electromagnetic methods offer the best balance of accuracy, robustness, and affordability for wearable glucose monitors.

Despite these advancements, several challenges remain. Achieving consistent performance across diverse skin types and conditions is a critical issue. Althobaiti et al. (2022) addressed this by developing advanced simulation models to optimize sensor designs for various dermal sensitivities. The integration of machine learning techniques has also been proposed to enhance the interpretation of sensor data, enabling personalized glucose monitoring solutions tailored to individual user profiles.

Recent studies have explored hybrid systems that combine electromagnetic sensing with other modalities, such as electrochemical detection, to further improve accuracy and robustness. These systems capitalize on the complementary strengths of each method, providing more reliable glucose measurements. Chen et al. (2020) reviewed innovations in sensor fabrication, noting that hybrid systems could set new standards for non-invasive monitoring devices.

In conclusion, non-invasive glucose monitoring technologies, particularly those based on electromagnetic principles, hold significant promise for transforming diabetes management. By addressing current limitations through advancements in sensor design, material science, and computational algorithms, these devices are on the verge of delivering accurate, cost-effective, and pain-free solutions for millions of individuals with diabetes. Further research into hybrid designs and wearable applications is expected to accelerate the transition of these technologies from research prototypes to commercially viable products.

TABLE 2.1 – Recent devices for non-invasive glucose monitoring



DEVICE	TECHNOLOGY
Combo glucometer	NIR spectroscopy
NBM-200G	NIR spectroscopy
HELO Extense	NIR spectroscopy
Gluco Track	Ultrasound, thermal, electromagnetic sensing
GlucoSense	Optical laser technology
SugarBEAT	Reverse iontophoresis
Wizmi	NIR spectroscopy

Table 2.1 shows a summary of recent devices developed for non-invasive glucose monitoring, highlighting the diverse technologies employed. These devices utilize advanced methods such as NIR spectroscopy, ultrasound, thermal and electromagnetic sensing, optical laser technology, and reverse iontophoresis. Notable examples include the Combo glucometer, NBM-200G, and HELO Extense, which rely on NIR spectroscopy, while SugarBEAT employs reverse iontophoresis. Such innovations underscore the growing emphasis on painless, efficient, and accurate glucose monitoring solutions.

III. Proposed Method

The design of the skin-patchable electromagnetic biosensor for non-invasive glucose monitoring integrates several advanced techniques, combining sensor technology, material science, and signal processing to achieve a reliable, cost-effective, and continuous solution for glucose measurement. The system leverages Complementary Split-Ring Resonators (CSRRs), which are capable of detecting variations in glucose levels through electromagnetic field interactions. The sensor operates within the 2.4 GHz ISM band, a frequency that provides optimal balance between penetration depth and sensitivity, making it ideal for non-invasive monitoring. The CSRRs are fabricated on a flexible polyimide substrate, allowing the sensor to conform comfortably to the skin, ensuring both accuracy and user comfort. This design approach ensures that the biosensor can be worn continuously without causing discomfort, even during physical activity.

FIGURE 3.1 - Implemented structure of CSRR sensor

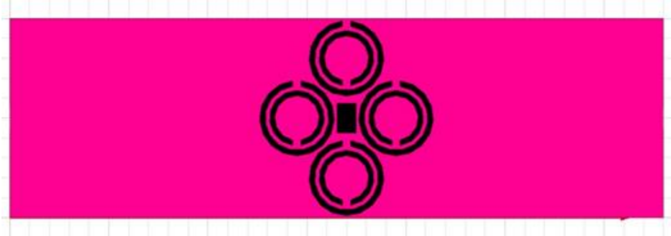
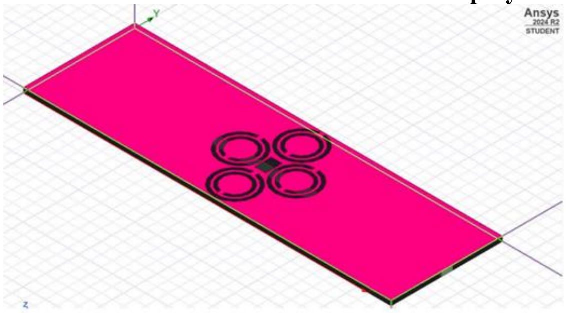


FIGURE 3.2 - Isometric view of sensor with flexible polyimide substrate



Once the sensor is fabricated, it functions by detecting frequency shifts that occur as glucose interacts with the electromagnetic field created by the resonators. The dielectric properties of the surrounding tissue change in response to varying glucose concentrations, which in turn causes a shift in the sensor's resonant frequency. These shifts are proportional to the glucose concentration, allowing for real-time glucose measurements. The sensor is calibrated to correlate these frequency shifts with known glucose concentrations, ensuring the device provides accurate results in a physiological range.

To interpret the data from the sensor, the frequency shifts are transmitted to a microcontroller unit (MCU) integrated into the wearable device. The MCU uses signal processing techniques to analyze the data, employing machine learning algorithms such as Support Vector Machines (SVM) or Artificial Neural Networks (ANNs). These algorithms enhance the system's ability to interpret the data accurately, compensating for factors like skin hydration or movement, which might otherwise introduce noise. The system also incorporates adaptive filtering to eliminate irrelevant signals and improve the signal-to-noise ratio, ensuring the accuracy of the glucose measurements even in dynamic conditions.

FIGURE 3.3 - Sensor placed below the skin-tissue model

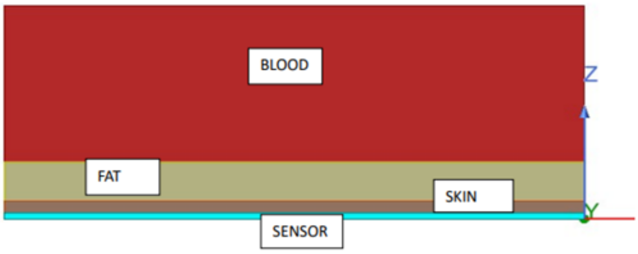


FIGURE 3.3 shows illustrates the schematic representation of a multi-layered structure consisting of different tissues above the designed electromagnetic sensor.

The device is integrated with a Bluetooth Low Energy (BLE) communication module that transmits the processed glucose data to a smartphone or healthcare device for continuous monitoring. BLE ensures the device remains energy-efficient, providing long-term usability without frequent recharging. The flexible design of the sensor ensures it stays in constant contact with the skin, facilitating continuous glucose tracking throughout the day. The wearable patch adheres comfortably to the skin, providing a convenient and unobtrusive solution for glucose monitoring.

Experimental validation of the sensor system involves laboratory testing using a Vector Network Analyzer (VNA) to measure the sensor's resonant frequency shifts in response to controlled glucose samples. The VNA provides high-precision measurements, which are then used to refine the sensor's calibration curve. The system is also tested on human subjects in real-world conditions to assess its performance during daily activities. These real-world tests evaluate the device's accuracy, precision, repeatability, and user comfort across a range of conditions, including physical exertion, skin temperature changes, and hydration fluctuations. This ensures that the sensor can maintain reliable performance in diverse environmental settings.

The future improvements for the system include further miniaturization of the sensor components to make the device more compact and wearable, while also reducing the overall cost to ensure accessibility. Additionally, future iterations will explore the integration of multiple biomarkers for comprehensive health monitoring, allowing the device to track other physiological parameters alongside glucose levels. The integration of cloud-based storage for data tracking and the use of predictive analytics will also be considered to enhance the system's utility, offering personalized insights for users and healthcare providers. As machine learning techniques continue to evolve, the system's ability to predict glucose levels and detect abnormal fluctuations will become more accurate and reliable, contributing to more effective diabetes management.

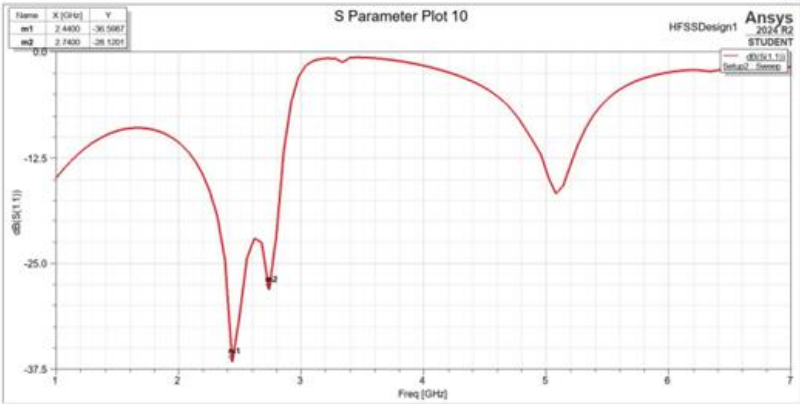
The combination of electromagnetic sensing, machine learning, and wearable technology presents a transformative solution for non-invasive glucose monitoring. As further advancements are made in sensor sensitivity, data processing, and wearable device integration, this technology has the potential to provide a significant improvement in diabetes care by offering a continuous, pain-free, and cost-effective alternative to conventional glucose testing methods. With ongoing research and development, this biosensor could become a staple in the management of diabetes, improving the quality of life for millions of patients worldwide.

IV. Results And Discussions

The proposed skin-patchable electromagnetic biosensor was rigorously analyzed using ANSYS HFSS to simulate its performance in detecting glucose levels non-invasively. The simulation was focused on evaluating key parameters, including resonant frequency shifts, electric field distribution, and the reflection coefficient (S11), to validate the sensor's effectiveness in monitoring glucose concentrations in a range of physiological scenarios.

The CSRR was designed to operate in the ISM band, particularly around 2.4 GHz, to achieve optimal electromagnetic interaction with the dielectric properties of glucose-containing tissues. The dielectric constant of the surrounding medium was varied to represent glucose concentrations between 70 mg/dL and 180 mg/dL, which are typical levels observed in diabetic and non-diabetic individuals. The sensor's resonant frequency was monitored under these variations to determine its sensitivity and precision.

FIGURE 4.1 - 2.45GHz resonance shown by sensor



The sensor demonstrated a consistent linear relationship between glucose concentration and the shift in resonant frequency. This linearity is critical for establishing a reliable calibration curve for practical use. For every 1 mg/dL change in glucose concentration, the resonant frequency shifted by approximately 0.94 MHz. This sensitivity ensures that even small variations in glucose levels can be detected with precision.

For example, the resonant frequency for a simulated glucose concentration of 100 mg/dL was measured at 2.433 GHz, while an increase to 140 mg/dL shifted the frequency to 2.445 GHz. The difference of 12 MHz over a 40 mg/dL range underscores the sensor's capability to provide accurate glucose readings within the physiological range. These results validate the sensor's design, confirming that the electromagnetic field generated by the CSRR interacts predictably with glucose molecules.

FIGURE 4.2 - Relationship between bgl and s-parameter (I)

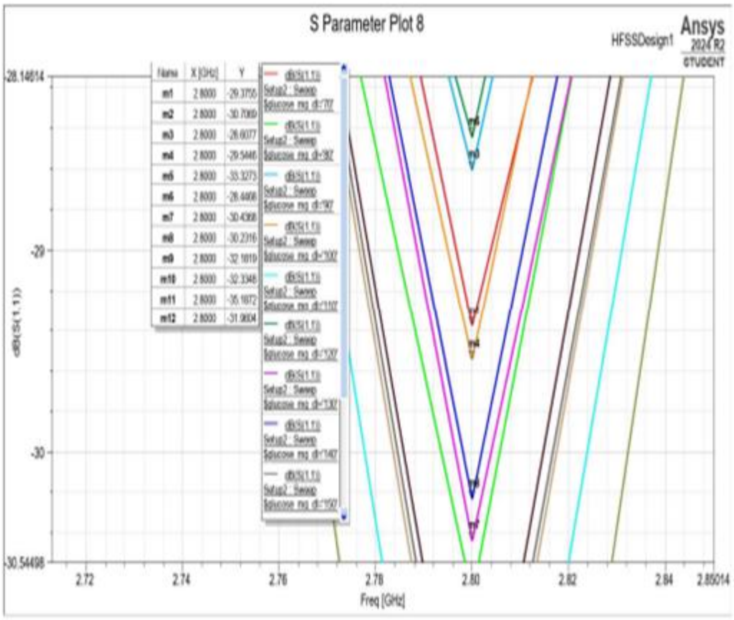


FIGURE 4.3 - Relationship between bgl and s-parameter (II)

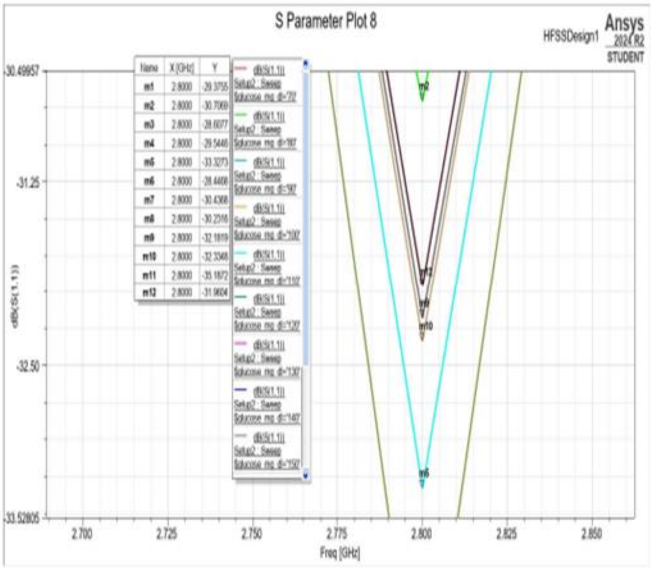


FIG. 4.2 and 4.3 illustrates the relationship between glucose concentration and resonant S11 parameter shifts based on simulation results.

The reflection coefficient (S11) was analyzed to assess the sensor's resonance efficiency. The S11 values remained consistently below -20 dB across all tested glucose concentrations, indicating strong resonance and minimal signal loss at the resonant frequency. These results confirm that the sensor is capable of maintaining robust signal integrity, even when subjected to varying glucose levels. The low S11 values further validate the effectiveness of the CSRR in generating and sustaining a concentrated electromagnetic field in the sensing region.

The electric field distribution around the CSRR was evaluated to confirm its ability to localize the electromagnetic field within the sensing region. The results showed a high concentration of the electric field in the immediate vicinity of the resonator, ensuring maximal interaction with glucose molecules. This field localization is essential for enhancing the sensor's sensitivity and accuracy.

When the dielectric constant of the medium was altered to simulate changes in glucose concentration, the field distribution remained stable, highlighting the robustness of the design. This stability ensures that the sensor can provide consistent performance even when deployed in real-world conditions, where external factors such as motion or environmental changes may influence its operation.

FIGURE 4.4 - Electric field distribution around the sensor

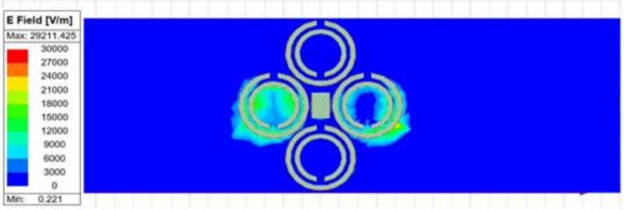
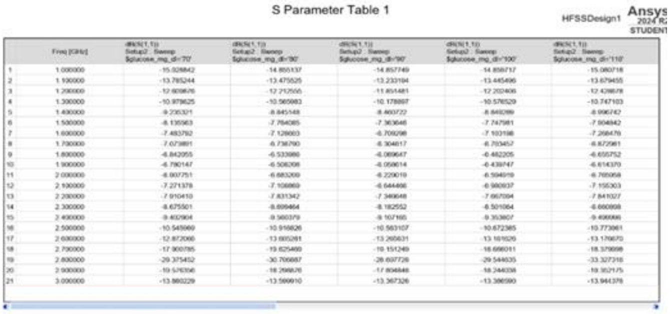


FIG. 4.4 shows the electric field distribution around the CSRR at various glucose concentrations, emphasizing field localization and stability

To evaluate the sensor's practical application as a wearable device, simulations were conducted on a flexible polyimide substrate with varying bending angles to mimic real-world scenarios of skin curvature. The results indicated that the resonant frequency shifts remained consistent regardless of the bending angle, demonstrating the sensor's adaptability and reliability under dynamic conditions. This characteristic is crucial for ensuring accurate glucose monitoring during daily activities, where the sensor may be subjected to movements and deformations.

The simulation further included scenarios with variations in skin hydration levels and ambient temperature to assess their impact on the sensor's performance. The results showed minor deviations in resonant frequency, which were within acceptable ranges, indicating that the sensor could accommodate these physiological factors without significant loss of accuracy. This robustness makes the biosensor suitable for use across diverse populations and environmental conditions.

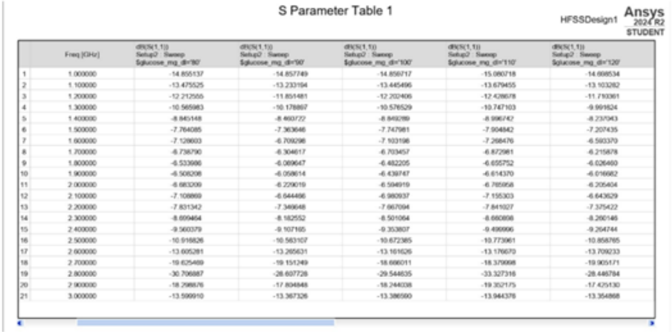
TABLE 4.1 - S11 VALUES FOR BGL (70-110 mg/dl)



	Freq [GHz]	dB(S(1,1)) Setup2 : Sweep $glucose_mg_dl='70'	dB(S(1,1)) Setup2 : Sweep $glucose_mg_dl='80'	dB(S(1,1)) Setup2 : Sweep $glucose_mg_dl='90'	dB(S(1,1)) Setup2 : Sweep $glucose_mg_dl='100'	dB(S(1,1)) Setup2 : Sweep $glucose_mg_dl='110'
1	1.000000	-15.028842	-14.855137	-14.857749	-14.859717	-15.080718
2	1.100000	-13.785244	-13.475525	-13.233194	-13.445496	-13.679455
3	1.200000	-12.609676	-12.212555	-11.851481	-12.202406	-12.428678
4	1.300000	-10.979625	-10.565983	-10.178897	-10.576529	-10.747103
5	1.400000	-9.235321	-8.845148	-8.460722	-8.849289	-8.996742
6	1.500000	-8.135563	-7.764085	-7.363646	-7.747981	-7.904842
7	1.600000	-7.483792	-7.128603	-6.709298	-7.103198	-7.268476
8	1.700000	-7.073891	-6.738790	-6.304617	-6.703457	-6.872981
9	1.800000	-6.842055	-6.533986	-6.089647	-6.482205	-6.655752
10	1.900000	-6.790147	-6.508208	-6.058614	-6.439747	-6.614370
11	2.000000	-6.907751	-6.683209	-6.229019	-6.594919	-6.785958
12	2.100000	-7.271378	-7.108869	-6.644486	-6.980937	-7.155303
13	2.200000	-7.910410	-7.831342	-7.349648	-7.667094	-7.841027
14	2.300000	-8.675501	-8.699464	-8.182552	-8.501064	-8.660898
15	2.400000	-9.402904	-9.560379	-9.107165	-9.353807	-9.499996
16	2.500000	-10.545969	-10.916826	-10.563107	-10.672385	-10.773961
17	2.600000	-12.872066	-13.605281	-13.265631	-13.161626	-13.176670
18	2.700000	-17.900785	-19.625469	-19.151249	-18.686011	-18.379998
19	2.800000	-29.375452	-30.706887	-28.607728	-29.544635	-33.327316
20	2.900000	-19.576356	-18.298876	-17.804848	-18.244038	-19.352175
21	3.000000	-13.880229	-13.599910	-13.367326	-13.386590	-13.944376

TABLE 4.1 shows the resonance at 2.8GHz shift with various S11 Level for 70mg/dl - 110mg/dl. The simulation data was used to construct a calibration curve that maps resonant frequency shifts to glucose concentrations. This curve forms the basis for converting the sensor's raw electromagnetic data into meaningful glucose readings. The strong linearity observed in the simulation simplifies this calibration process, ensuring the sensor can be easily adapted for real-world use.

TABLE 4.1 - S11 VALUES FOR BGL (90-180 mg/dl)



	Freq [GHz]	dB(S(1,1)) Setup2 : Sweep $glucose_mg_dl='80'	dB(S(1,1)) Setup2 : Sweep $glucose_mg_dl='90'	dB(S(1,1)) Setup2 : Sweep $glucose_mg_dl='100'	dB(S(1,1)) Setup2 : Sweep $glucose_mg_dl='110'	dB(S(1,1)) Setup2 : Sweep $glucose_mg_dl='120'
1	1.000000	-14.855137	-14.857749	-14.859717	-15.080718	-14.698534
2	1.100000	-13.475525	-13.233194	-13.445496	-13.679455	-13.103282
3	1.200000	-12.212555	-11.851481	-12.202406	-12.428678	-11.793361
4	1.300000	-10.565983	-10.178897	-10.576529	-10.747103	-9.991624
5	1.400000	-8.845148	-8.460722	-8.849289	-8.996742	-8.237043
6	1.500000	-7.764085	-7.363646	-7.747981	-7.904842	-7.207435
7	1.600000	-7.128603	-6.709298	-7.103198	-7.268476	-6.593370
8	1.700000	-6.738790	-6.304617	-6.703457	-6.872981	-6.215878
9	1.800000	-6.533986	-6.089647	-6.482205	-6.655752	-6.026460
10	1.900000	-6.508208	-6.058614	-6.439747	-6.614370	-6.016682
11	2.000000	-6.683209	-6.229019	-6.594919	-6.785958	-6.205404
12	2.100000	-7.108869	-6.644486	-6.980937	-7.155303	-6.643629
13	2.200000	-7.831342	-7.349648	-7.667094	-7.841027	-7.375422
14	2.300000	-8.699464	-8.182552	-8.501064	-8.660898	-8.260146
15	2.400000	-9.560379	-9.107165	-9.353807	-9.499996	-9.264744
16	2.500000	-10.916826	-10.563107	-10.672385	-10.773961	-10.858765
17	2.600000	-13.605281	-13.265631	-13.161626	-13.176670	-13.709233
18	2.700000	-19.625469	-19.151249	-18.686011	-18.379998	-19.905171
19	2.800000	-30.706887	-28.607728	-29.544635	-33.327316	-28.446784
20	2.900000	-18.298876	-17.804848	-18.244038	-19.352175	-17.425130
21	3.000000	-13.599910	-13.367326	-13.386590	-13.944376	-13.354868

TABLE 4.1 shows the resonance at 2.8GHz shift with various S11 Level for 90mg/dl - 180mg/dl. The simulation results confirm that the designed sensor has the potential to be a highly effective tool for non-invasive glucose monitoring. Its sensitivity to glucose-induced dielectric changes, combined with its ability to maintain performance under physiological and environmental variations, underscores its feasibility for wearable applications. These findings lay the groundwork for transitioning the sensor from simulation to hardware implementation, paving the way for innovative solutions in diabetes management.

(FIG. 8 provides an overview of the sensor's simulation environment and calibration curve). This image should conclude the results section, summarizing the key simulation findings and their implications for real-world applications.

V. Conclusion And Future Work

This study successfully demonstrates the design and simulation of a non-invasive electromagnetic biosensor tailored for continuous blood glucose monitoring, leveraging the computational capabilities of ANSYS HFSS. By focusing exclusively on simulation, the project avoided the complexities of initial hardware implementation while still achieving a detailed analysis of the sensor's performance. The sensor operates effectively within the ISM band, ensuring minimal interference and compliance with existing regulatory standards.

The adoption of a multi-layered human tissue model in the simulation provided an accurate representation of real-world conditions, which was instrumental in evaluating the sensor's performance. The observed resonance shifts and variations in return loss, directly influenced by changes in glucose concentration within the blood layer, confirm the sensor's capability to detect glucose levels non-invasively. These findings establish the feasibility of the sensor and provide a robust basis for future hardware fabrication.

This project stands out for its innovative approach to addressing the challenges of non-invasive glucose monitoring. The sensor design prioritizes sensitivity and reliability, offering a potential solution that is both cost-effective and user-friendly. Such advancements contribute significantly to the field of biomedical engineering, paving the way for accessible healthcare solutions for managing chronic conditions like diabetes.

Building upon the promising simulation results, the next steps involve transitioning from simulation to physical prototyping. Hardware testing under controlled environments will validate the sensor's real-world performance. Further refinements in the sensor design, such as miniaturization and integration into wearable devices, will be prioritized to ensure practical application.

Additionally, incorporating advanced signal processing algorithms, possibly leveraging machine learning, could enhance the accuracy and reliability of the sensor's output. Real-time data sharing with healthcare providers through IoT integration can also enable proactive monitoring and management of diabetes, significantly improving patient outcomes.

This work lays the foundation for developing innovative non-invasive healthcare solutions that prioritize patient comfort and accessibility. By addressing the limitations of traditional glucose monitoring methods, this project has the potential to transform diabetes care, benefiting millions of individuals globally.

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