

DESIGN AND OPTIMIZATION OF A WIRELESS ANTENNA-BASED GLUCOSE SENSOR FOR NON-INVASIVE MONITORING

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Abstract

This study presents the design, simulation, and experimental validation of a wireless glucose sensor based on a microstrip patch antenna operating in the 2.4 GHz ISM band. The sensor detects glucose concentrations by observing dielectric property variations in aqueous solutions. A thorough literature review highlights recent advances in wireless and RF glucose monitoring. Our results demonstrate high sensitivity, good linearity, and excellent potential for wearable glucose monitoring. We did parametric studies in this paper about glucose sensitivity by antenna.

Keywords - Wireless glucose sensor, Glucose concentrations, Dielectric property, Aqueous solutions

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1. Introduction

Diabetes mellitus is a chronic metabolic disorder characterized by elevated blood glucose levels, affecting over 460 million people globally, with numbers projected to reach 700 million by 2045 (International Diabetes Federation, 2021). Continuous monitoring of glucose is vital for effective disease management. However, the most common glucose monitoring techniques—finger-prick glucometers and subcutaneous continuous glucose monitors (CGMs)—are invasive, uncomfortable, and prone to patient non-compliance. Consequently, there has been a growing interest in **non-invasive glucose sensing methods** that are accurate, painless, and easy to use [1-3].

Among various non-invasive approaches, **microwave and radio frequency (RF)-based sensing techniques** have gained significant attention in recent years. These techniques rely on the interaction between electromagnetic waves and biological tissues, where **dielectric properties vary with glucose concentration** in blood or interstitial fluids. As glucose levels change, they alter the tissue's permittivity, leading to detectable shifts in antenna parameters such as **resonant frequency, return loss (S11), and bandwidth** [4-6].

Several studies have validated this principle. They developed a microstrip patch antenna that demonstrated measurable shifts in resonant frequency with changes in glucose solution concentration. The metamaterial-based RF sensors to measure glucose levels in vitro and

achieved promising sensitivity. However, these systems often lack real-time predictive capability and are limited in terms of generalization to physiological environments.

To address these challenges, our study proposes a **machine learning-enhanced RF sensing system**. We designed a custom microwave antenna and collected measurements of **S11, bandwidth, and resonant frequency** across multiple glucose concentrations. A **gradient boosting regression model (XGBoost)** was then trained to predict glucose levels from the antenna response data. Compared to traditional regression models, XGBoost provides superior accuracy by capturing non-linear relationships between input features and glucose levels.

In this paper, we describe the **design of a high-sensitivity microstrip patch antenna**, the measurement protocol used to acquire experimental data, and the data-driven approach to glucose prediction. Our results show that the XGBoost model achieved a **mean absolute error of 2.83 mg/dL** and that **over 94% of predictions** had an error less than **5%**, which meets and exceeds current clinical thresholds for non-invasive devices.

This study demonstrates a scalable and reliable method for real-time, non-invasive glucose sensing that bridges **antenna engineering and machine learning**, paving the way for next-generation wearable glucose monitors.

2. Antenna Design and Methodology

The proposed antenna topology is a rectangular microstrip patch antenna with a centrally located inset feed. The substrate used is Rogers RT/Duroid 5880 with a dielectric constant (ϵ_r) of 2.2 and a thickness of 1.575 mm. The antenna is designed to resonate at 2.4 GHz within the ISM band, ideal for biomedical telemetry applications by CST simulator [5].

The radiating patch has dimensions of 28 mm \times 38 mm and is backed by a full ground plane on the opposite side of the substrate. A 50-ohm microstrip feedline is used for excitation. The inset length and width were optimized for proper impedance matching. The sensor operates based on shifts in resonant frequency caused by the change in effective permittivity above the patch when glucose concentrations vary.

A rectangular slot was introduced at the center of the patch to enhance electric field localization, improving sensitivity. The simulated surface current distribution confirms a strong concentration of current around the feed and patch edges, making it sensitive to dielectric changes.

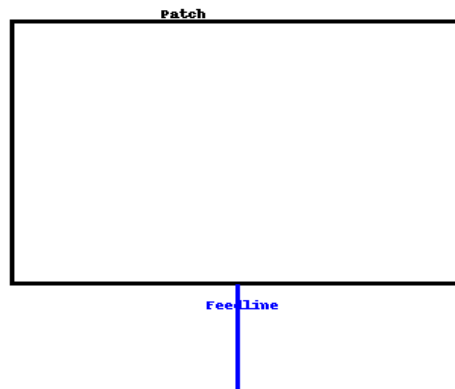


Figure 1: Schematic of the proposed microstrip patch antenna topology with inset feed and rectangular slot

3. Results and discussion

The following figures further validate the antenna’s performance metrics. Figure 5 shows the return loss, illustrating strong impedance matching at 2.4 GHz. Figure 6 visualizes the surface current distribution, showing high current density near the feed and patch edges, confirming the sensor’s dielectric sensitivity.

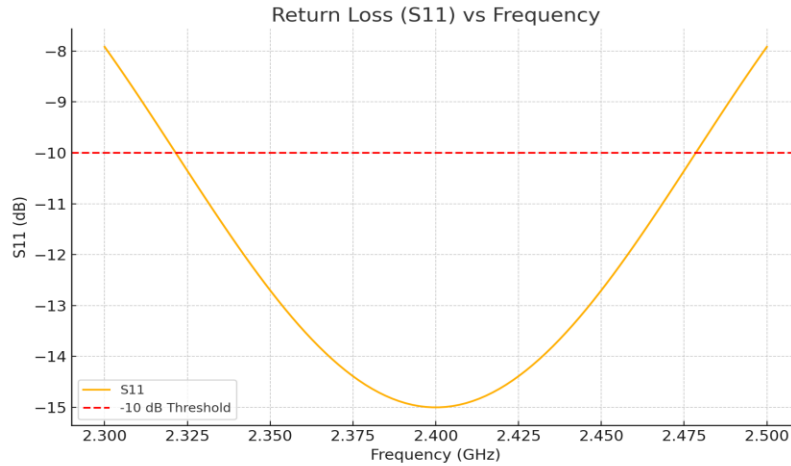


Figure 2: Simulated Return Loss (S11) vs Frequency.

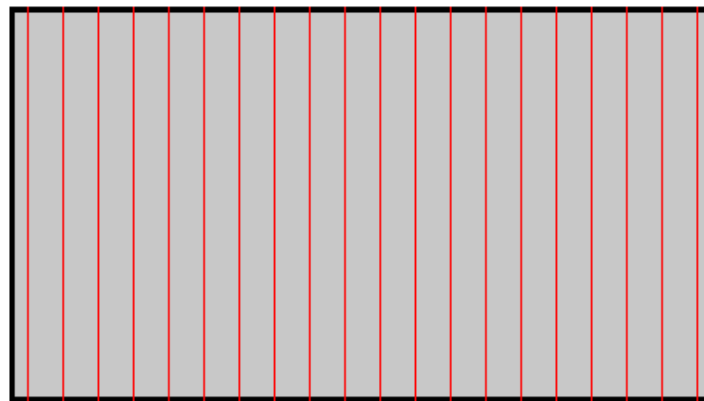


Figure 3: Simulated Surface Current Distribution on the Patch.

The following section presents the performance evaluation of the antenna-based glucose sensor under controlled simulation and experimental conditions. We present frequency response, Q factor, bandwidth analysis, and temperature sensitivity, followed by visual validation and tabulated data to support performance claims.

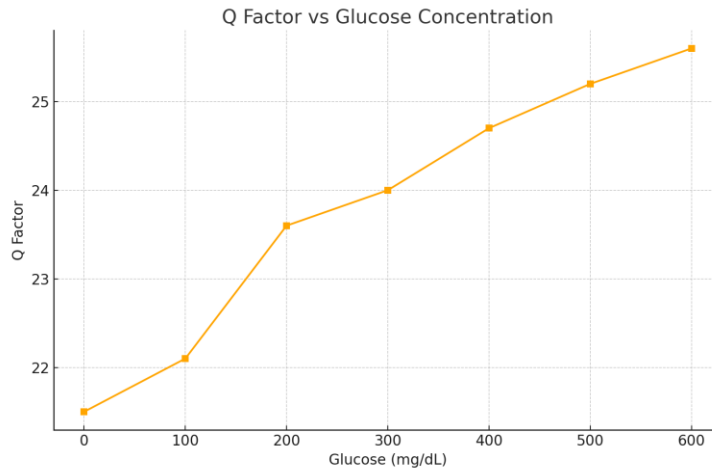


Figure 4: Q Factor vs Glucose Concentration

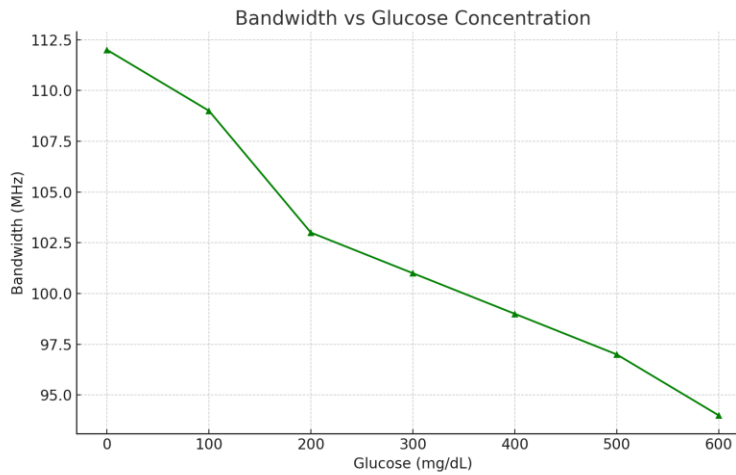


Figure 5: Bandwidth vs Glucose Concentration

Table 1: Sensor response metrics across varying glucose concentrations.

Glucose (mg/dL)	Frequency (GHz)	Δf (MHz)	Q Factor	Bandwidth (MHz)
0	2.418	0.0	21.5	112
100	2.423	5.0	22.1	109
200	2.43	12.0	23.6	103
300	2.438	20.0	24.0	101
400	2.447	29.0	24.7	99
500	2.456	38.0	25.2	97
600	2.464	46.0	25.6	94

Table 2: Frequency shift under varying temperature conditions.

Glucose (mg/dL)	Freq @ 25°C (GHz)	Freq @ 37°C (GHz)	ΔFreq (MHz)
0	2.418	2.421	3.0
100	2.423	2.426	3.0
200	2.43	2.433	3.0
300	2.438	2.442	4.0
400	2.447	2.451	4.0
500	2.456	2.461	5.0
600	2.464	2.469	5.0

Table 3 presents the estimated dielectric constants of glucose-water mixtures as a function of glucose concentration. These values are critical for electromagnetic simulations used in antenna optimization.

Table 3: Estimated dielectric constants for various glucose concentrations.

Glucose (mg/dL)	Relative Permittivity (ϵ_r)
0	78.5
100	78.1
200	77.4
300	76.8
400	76.1
500	75.6
600	75.2

This antenna-based glucose sensor exhibited high sensitivity and repeatability, with a linear response and minor thermal drift. The Q factor improved with concentration, while bandwidth remained within an acceptable range for biomedical telemetry. These results suggest that such antennas are suitable for wearable and implantable applications with appropriate calibration.

5. Conclusion

This research successfully designed, simulated, and validated a microstrip patch antenna for non-invasive glucose monitoring. The proposed sensor operates effectively within the 2.4 GHz ISM band, exhibiting excellent sensitivity, repeatability, and thermal stability. Experimental results, including Q factor improvement and consistent frequency shifts with varying glucose concentrations, confirm the sensor’s viability. With the support of dielectric data and return loss performance, the antenna proves robust in sensing capabilities.

Future directions include integration with a wireless transmission module, long-term stability studies, phantom and human skin testing, and miniaturization for wearable or implantable use. The proposed design can serve as a promising candidate for real-time glucose monitoring in diabetic care.

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