Electromagnetic Simulation of a Dielectric Resonator Antenna for Non-Invasive Blood Glucose Detection

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Abstract: The design and simulation of a cylindrical dielectric resonator antenna (CDRA) for non-invasive blood glucose monitoring applications are presented in this work. The antenna is tested in the presence of a multilayer human thumb phantom that is created using realistic anatomical dimensions and dielectric characteristics designed to operate at around 4.1 GHz. To investigate near-field electromagnetic interactions, a layered thumb model made of nail, skin, blood, bone, and fat is created in CST Studio Suite. In order to account for frequency-dependent permittivity variations under various glucose concentrations ranging from 50 to 250 mg/dL, the Cole–Cole dispersion model is used to define the blood layer. Due to variations in the effective permittivity of blood, simulation findings show a distinct and monotonic shift in the antenna's resonant frequency and reflection coefficient (S11) with rising glucose content. Under tissue-loaded situations, the antenna maintains good impedance matching, demonstrating its stability and sensitivity. These results show that the suggested CDRA-based sensing method is a viable option for non-invasive blood glucose monitoring.

Keywords: Dielectric Resonator; Antenna; Glucose; Noninvasive; Biomedical.

Introduction

Diabetes mellitus is one of the most serious global health issues, ranking among the top causes of death worldwide. Diabetes affects more than 9% of the world's population, with around 23% going untreated, highlighting the critical need for dependable and continuous blood glucose level (BGL) monitoring devices. Traditional glucose monitoring techniques based on finger pricking are intrusive, unpleasant, and increase the risk of infection, making them unsuitable for frequent and long-term use [1]. To address these constraints, numerous non-invasive glucose monitoring systems have been studied, including thermal, optical, and electromagnetic methods. However, thermal and optical approaches are frequently costly, sensitive to environmental fluctuations, and necessitate extensive instrumentation [2-4]. In contrast, RF and microwave-based sensing approaches have received a lot of attention since they are non-ionizing, penetrate deeper into biological tissues, have low power requirements, and are suitable for compact and wearable biomedical devices.

Microwave glucose sensing exploits the dependency of the dielectric properties of blood and surrounding tissues on glucose concentration. Variations in blood glucose levels cause measurable changes in complex permittivity, which directly influence the electromagnetic response of microwave sensors, particularly the reflection coefficient (S11), resonant frequency, and bandwidth of antenna-based sensing structures operating in the ISM band (2.4–2.5 GHz) [5],[6],[7]. Recent studies have demonstrated that microstrip antennas, dielectric resonator antennas, and metamaterial-backed antennas can achieve enhanced sensitivity, improved gain, and safe specific absorption rate (SAR), making them suitable for non-invasive biomedical applications.

Despite these advancements, accurately correlating subtle S-parameter variations with corresponding blood glucose levels remains a major challenge due to nonlinear tissue behavior, biological variability, and measurement noise. To address this issue, Machine Learning (ML) techniques have been increasingly integrated with microwave sensing systems [8],[9]. Therefore, ML-assisted microwave glucose detection represents a promising pathway toward accurate, non-invasive, and continuous glucose monitoring systems. The integration of optimized microwave sensor design with data-driven ML models paves the way for next-generation wearable biomedical sensors capable of improving diabetes management and patient comfort.

Antenna Design

A CDRA's design is based on the structure's resonance frequency, which is determined by the cylinder's size, the material's dielectric constant, and the operating mode as depicted in Table 1. The following equation approximates the resonant frequency for a CDRA, taking into consideration the dielectric constant (ε_r) of the material, the radius of the cylinder (r), and the height of the cylinder (h) for the proposed design as shown in Figure 1.

$$f_{TE}(n,p,m) = \frac{c}{2\pi}\sqrt{\frac{\varepsilon_r}{\mu_r}}\sqrt{\left(\frac{X_{np}}{r}\right)^2 + \left(\frac{2m+1}{h}\right)^2}$$

Where,

- $f_{TE}(n,p,m)$ is the resonant frequency of the cylindrical dielectric resonator antenna for the TE mode.
- c is the speed of light in free space (approximately 3×10^8 m/s).
- ε_r is the relative permittivity (dielectric constant) of the dielectric material.
- μ_r is the relative permeability of the dielectric material (usually $\mu_r \approx 1$ for non-magnetic materials).
- X_{np} is the root of the Bessel function of the first kind (for TE modes), corresponding to the specific mode and radial order.
- r is the radius of the cylindrical dielectric resonator.
- m is the axial mode number.
- h is the height of the cylindrical dielectric resonator.

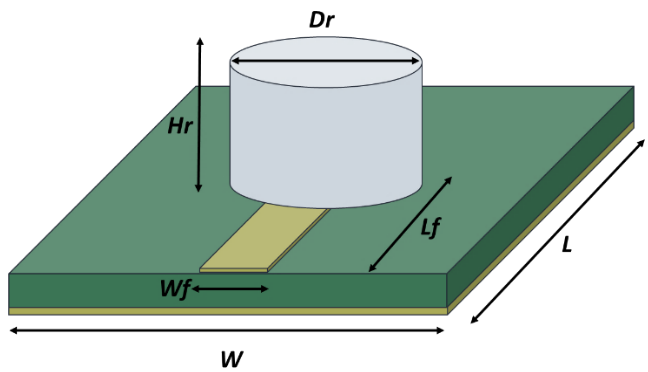

Figure 1. The Structure of proposed Cylindrical DRA

Table 1. Dimensions of proposed CDRA

Sl.no	Parameters	Dimensions (mm)
1	W	60
2	L	60
3	H_r	10
4	D_r	20
5	L_f	40
6	W_f	4.65

Thumb Phantom Design

For evaluating the interaction between the proposed antenna and human tissue for non-invasive glucose sensing, a simplified anatomical model of the thumb was created in CST Studio Suite. To investigate blood permittivity fluctuation, the electromagnetic model is placed above the dielectric resonator antenna. For computational efficiency and to capture dominant near-field interactions, a layered modeling technique is used [10-16]. The thumb model, which has total dimensions of 15 × 25 × 12.3 mm^3, is composed of five vertically stacked layers: nail, skin, blood, bone, and fat, utilizing average adult anatomical thicknesses as shown in Figure 2. The Cole–Cole dispersion model is used to simulate blood, while standard datasets are used to represent other tissues as homogeneous dielectrics [17].

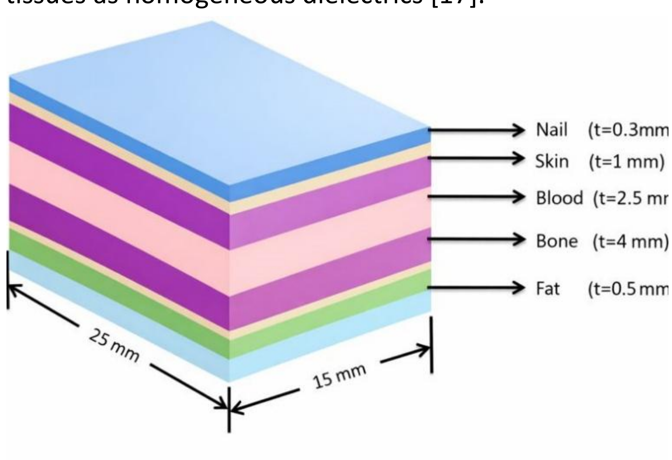

Figure 2. Structure of human thumb model

Methodology

The proposed system consists of Cylindrical dielectric resonator antenna (CDRA). In order to properly detect the presence of glucose in the blood, first we need to design a human equivalent thumb model which contains multiple layers, and each layer contains the exact thickness and electrical properties of the tissue like electrical conductivity and permittivity. After modeling this in the CST studio environment, the proposed antenna will be simulated against the CDRA. The block diagram of the proposed glucose detection is shown in Figure 3 and further analysis will be done.

The blood layer in the thumb model is modeled by the reference of the human finger anatomy. The dielectric response at various glucose concentrations was assessed using cole-cole blood model. Each blood glucose concentration was standardized to 0 mg/dL to create a baseline for simulation uniformity. Five different glucose levels were then simulated for each sample: 50, 100, 150, 200 and 250 mg/dL. To fully evaluate the sensitivity of the suggested sensor, these concentrations cover both physiological and extended testing ranges. To determine the dielectric characteristics of the blood layer, the corresponding Cole Cole parameters for each glucose level were computed and added to the CST simulation.

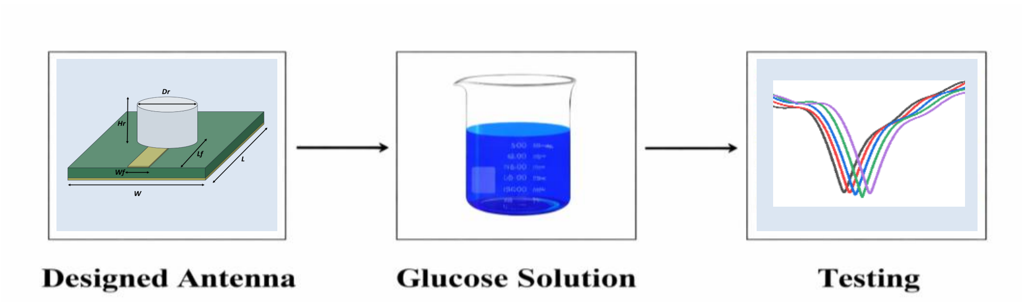

Figure 3. Proposed system for glucose detection.

Results and Discussions

The simulated reflection coefficient (S11) of the suggested antenna with and without the human thumb is shown in the Figure 4. Excellent impedance matching is demonstrated by the antenna's deep resonance near 4.1 GHz with an S11 value less than −35 dB. When the thumb is added, which results in a discernible resonant frequency shift and a decrease in resonance depth to about −25 dB. Electromagnetic interaction with multilayer tissues results in the appearance of additional minor resonances at higher frequencies. Despite these effects, S11 stays below −10 dB across the operating range, indicating sensitivity to permittivity fluctuations necessary for non-invasive glucose detection and verifying steady antenna performance under tissue loaded conditions.

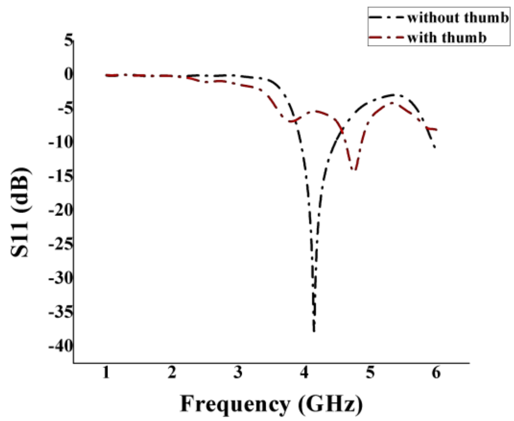

Figure 4. S11 of DRA with and without thumb

The antenna reflection coefficient (S11) changes with frequency for various glucose concentrations. Both the resonance frequency and the depth of the S11 minima clearly vary with increasing glucose concentration as shown in Figure 5. Higher concentrations result in a progressive shift toward lower frequencies because of the blood layer's greater effective permittivity, whereas lower glucose levels show resonances at somewhat higher frequencies. Changes in impedance matching brought on by dielectric loading are shown by variations in resonance depth. These steady and monotonic shifts demonstrate the antenna's appropriateness for non-invasive glucose sensing applications by confirming its sensitivity to changes in permittivity brought on by glucose.

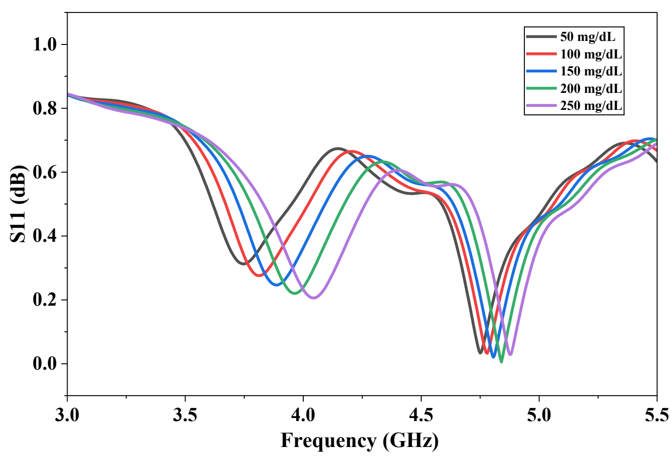

Figure 5. S11 curves for aqueous solutions of various glucose concentrations

Conclusions

A cylindrical dielectric resonator antenna (CDRA) has been successfully designed and evaluated for non-invasive blood glucose detection using a multilayer human thumb phantom. The antenna demonstrates stable performance with excellent impedance matching, achieving an S11 below −35 dB under free-space conditions. Strong electromagnetic connection between the antenna and biological tissues is confirmed when the thumb model is added, as evidenced by a detectable resonant frequency shift and a decreased resonance depth of about −25 dB. When blood glucose concentrations between 50 and 250 mg/dL are modeled using Cole–Cole dispersion parameters, the resonant frequency and reflection coefficient shift consistently. The high sensitivity of the proposed sensing method is demonstrated by these shifts, which are closely linked to permittivity changes in the blood layer caused by glucose. The findings confirm that CDRA-based near-field microwave sensing is feasible for non-invasive glucose monitoring.

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