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Option: Instrumentation  
**Theme**

# SIMULATION AND DESIGN OF BIOSENSOR FOR BLOOD GLUCOSE CONCENTRATION DETECTION.

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## ***LIST OF ABBREVIATIONS***

ELF	extremely-low-frequency
RF	radio frequency
MW	microwave
VNA	Vector Network Analyzer
ISFET	ion-sensitive field-effect transistor
DNA	deoxyribonucleic acids
ECL	electrochemiluminescence
ANN	artificial neural network
SRR	Split-Ring Resonator

# GENERAL INTRODUCTION

Diabetes mellitus is one of the most pervasive and life-threatening chronic diseases in the world today. It affects over 200 million individuals globally, a number expected to increase by six million every year. Effective management of diabetes hinges on frequent monitoring of blood glucose levels, yet the currently widespread testing methods are often costly and requiring multiple finger-prick tests daily. These limitations have intensified the global demand for non-invasive, real-time, and accurate blood glucose monitoring systems.

Recent advances in biosensor technology, especially those leveraging electromagnetic (EM) sensing, offer a promising solution. EM sensors detect variations in the dielectric properties of biological fluids such as blood, which change according to glucose concentration. Within this domain, metamaterial-inspired resonators have emerged as highly sensitive and cost-effective platforms for glucose detection. These sensors function by measuring perturbations such as shifts in resonant frequency when a sample is introduced to the sensing structure.

This project focuses on the simulation and design of a metamaterial-based biosensor specifically engineered for the detection of blood glucose concentrations. The proposed design utilizes split-ring resonators (SRRs) operating at millimeter-wave (mm-w) frequencies. These frequencies enable the detection of subtle changes in blood composition with high sensitivity and stability.

The biosensor structure is modeled and simulated using electromagnetic software, where blood samples with varying glucose levels (ranging from 40 mg/dL to 200 mg/dL) are represented using Debye model parameters to capture their complex frequency-dependent dielectric behavior.

The thesis is structured into three core chapters:

**chapter 1** delves into the general notions on electromagnetism in biosensing applications, frequency spectrum analysis scattering parameters, metamaterials and its use in sensor sensitivity enhancement



Expanding on this foundation, **Chapter 2** investigates the integration of biosensors the detection of blood glucose concentrations: Definitions of Biosensors, History of Biosensors , Characteristics, Classification and Applications.

**Chapter 3** centers on the simulation and design of a metamaterial-based biosensor specifically engineered for the detection of blood glucose concentrations. This chapter meticulously presents and scrutinizes all simulation results.

In summary, our study aims to design a biosensor for the detection of blood glucose concentrations. This study targets to develop a robust and efficient diagnostic tool that can significantly improve early detection and treatment outcomes for patients .

# ***CHAPTER 1:***

## ***GENERAL NOTIONS***

## 1.1 Introduction

This chapter introduces the essential physical and electromagnetic principles that underpin modern biosensor design. By establishing a clear understanding of these general notions, the reader will be better equipped to grasp the simulation techniques and design methodologies discussed in later chapters.

## 1.2 Biosensing and Its Importance

The rising global prevalence of diabetes has created an urgent need for reliable, accurate, and continuous monitoring of blood glucose levels. Traditional glucose monitoring systems often require invasive techniques and are limited by low sensitivity or delayed response times. In response to these challenges, biosensors have emerged as promising tools, offering real-time, non-invasive, and cost-effective solutions for glucose detection.

At the core of advanced biosensor design lies a multidisciplinary integration of physics, materials science, and biomedical engineering. Among the key physical concepts, **electromagnetism, frequency spectrum analysis, scattering parameters, and metamaterials** play a fundamental role in understanding and enhancing sensor performance. These concepts provide the theoretical foundation for developing highly sensitive and specific glucose biosensors, particularly in designs that leverage electromagnetic waves or novel materials to detect biological variations.

## 1.3 Electromagnetism in Biosensing Applications

Magnetic bio-detection constitutes a large area of research and development driven by its potential to provide versatile diagnostic tools in biology and medicine. Specific sensing technology is used depending on the applications which can be subdivided in two main groups: measuring a magnetic field from people and detecting magnetically labelled bio substances. The human body is mostly composed of what is normally regarded as nonmagnetic materials. In reality, every substance has some magnetic sensitivity, however small, being paramagnetic or diamagnetic. Their response is greatly limited by thermal fluctuations. In addition to this there is a further source of a magnetic field due to the neural activity which operates continuously throughout a living body. This neural activity involves movement of electric charges and, as such gives rise to magnetic fields. In principle, these

fields represent a description of the neural activity and can be studied to help understanding the workings of the human body as well as provide an aid to diagnosis.

### 1.3.1 Maxwell's Equations and Wave Propagation

the mathematical representation of EM-wave interaction with dielectrics. We know that application of electric field leads to displacement of charges in a dielectric, inducing dipoles. The average dipole moment ( $\mu$ ), with charge  $q$  and charge separation  $x_i$  is given by Equation (1.1):

$$\mu = qx_i \quad (1.1)$$

Polarization density ( $P$ ) is the sum of all such dipole moments in a volume  $\delta v$  with  $N$  dipoles (Equation (1.2))

$$P = \frac{\sum_{i=1}^N qx_i}{\delta v} \quad (1.2)$$

As given by Maxwell,  $P$  is the density of permanent and induced dipole moments in a system,  $D$  is the electric charge density vector also known as displacement field and accounts for the total charge in the system and the difference in vectors ( $D$  &  $P$ ) accounts for the remaining free charges in the dielectric, given as Equation (1.3):

$$D = \epsilon_0 E + P \quad (1.3)$$

Alternatively, the displacement density can be written as Equation (4):

$$D = \epsilon' \epsilon_0 E \quad (1.4)$$

where  $\epsilon_0$  denotes permittivity of free space and  $\epsilon'$  is relative permittivity. Combining Equations (1.3) and (1.4), we get Equation (1.5):

$$P = (\epsilon' - 1)\epsilon_0 E \quad (1.5)$$

Now, to obtain the dependence of permittivity ( $\epsilon_0$ ) on each type of polarization, we consider the polarization field ( $P$ ) to be made of  $N'$  individual dipole moments ( $\mu$ ), given as Equation (1.6):

$$P = \mu N' \quad (1.6)$$

The dipole moment can be assumed linear to the local field  $E'$  experienced by the dipole [6] (induced dipoles give rise to an induced field which opposes  $E$ , resulting in net field  $E'$ ), given as Equation (1.7):

$$\mu = \alpha_t E' \quad (1.7)$$

Where  $\alpha_t$  is the proportionality constant known as polarizability. Different polarization mechanisms contribute towards the total polarizability ( $\alpha_t$ ) of the dielectric, given as Equation (1.8):

$$\alpha_t = \alpha_e + \alpha_a + \alpha_d + \alpha_{MW} + \alpha_i, \quad (1.8)$$

Where  $\alpha_e$ ,  $\alpha_a$ ,  $\alpha_d$ ,  $\alpha_{MW}$  and  $\alpha_i$  are the electronic, atomic, dipolar, interfacial and ionic polarizabilities respectively. Combining Equations (1.5)–(1.7), we obtain Equation (1.9):

$$(\epsilon' - 1)\epsilon_0 E = \alpha_t E' N' \quad (1.9)$$

Equation (9) relates the macroscopic quantities  $\epsilon'$  and  $E$  to the molecular parameters  $E'$  &  $N'$ . We can note from Equation (9) that permittivity ( $\epsilon'$ ) depends on the number of mechanisms contributing towards total polarization (through  $\alpha_t$ ).

### 1.3.2 Interaction of Electromagnetic Fields with Biological Media :

The biological effects of electromagnetic fields and waves have been a subject of scientific research since the discovery of electromagnetic radiation and its first use in therapeutic applications more than 100 years ago. Since then, our knowledge regarding its effects on health has increased tremendously. Nevertheless, they have become the focus of much attention because of the expansion and distribution of electric power at 50 and 60 Hz in the extremely-low-frequency (ELF) spectrum (between 3 Hz and 3 kHz) and because of the accelerated use of RF radiation (300 MHz–6 GHz and beyond) in wireless communication in recent decades. A notable reason for the increased attention on the subject is the uncertainty and lack of understanding of the mechanism of interaction of electromagnetic fields and waves with biological systems. Although ELF fields and RF radiation are all part of the same known electromagnetic spectrum, the mode of coupling into biological tissues and mechanism of

interaction can be quite different for the two. This chapter discusses the coupling of electromagnetic fields and waves into biological systems. Clearly, regardless of the mechanism of interaction fields must be coupled into the system and energy must be transferred, absorbed, or deposited in the biological system in order for the system to respond in some manner. Thus, to gain a greater knowledge of biological responses, the electric, magnetic, or electromagnetic field that is effective in exerting its influence must be quantified and correlated with the observed effect.

## **1.4 Frequency Spectrum Analysis**

Frequency spectrum analysis plays a critical role in the development and optimization of biosensors, particularly those employing electromagnetic techniques for non-invasive glucose detection. By analyzing how different frequency bands interact with biological tissues, researchers can identify optimal ranges for signal penetration, sensitivity, and specificity. In the context of biomedical applications, radio frequency (RF) and microwave (MW) bands are particularly promising due to their ability to probe dielectric properties of tissues and fluids, which vary with glucose concentration. These frequency-dependent variations enable biosensors to detect even subtle changes in glucose levels by measuring signal reflection, absorption, or scattering. Selecting the appropriate frequency band is thus essential for achieving accurate and reliable biosensing performance, balancing factors such as tissue penetration depth, signal attenuation, and regulatory constraints.

### **1.4.1 RF and Microwave Frequencies in Biomedical Applications**

Radio Frequency (RF) and Microwave (MW) technologies have found extensive applications in biomedical fields due to their non-invasive nature and ability to interact with biological tissues. These frequencies are particularly useful in diagnostics, imaging, and therapeutic applications.

### **1.3.2 Frequency Bands Suitable for Glucose Detection**

Selecting the appropriate frequency band is crucial for effective glucose detection using RF/MW technologies. The interaction between electromagnetic waves and glucose molecules varies across different frequencies, influencing the sensitivity and accuracy of the detection.

Optimal Frequency Ranges:

- 2.4 GHz ISM Band:

This frequency is widely used in wireless communication technologies like Wi-Fi and Bluetooth. Studies have shown that glucose sensors operating around this frequency can achieve high sensitivity, making it suitable for integration with consumer-level RF circuitry.

- 58–62 GHz Band:

Millimeter-wave frequencies in this range have been explored for in vivo glucose monitoring. Research indicates that this band can detect glucose concentration changes through skin tissue, offering a non-invasive monitoring approach.

- 1.4 GHz to 5 GHz Range:

Sensors operating within this range have demonstrated the ability to detect glucose concentrations in aqueous solutions, with resonance shifts corresponding to glucose levels. This frequency range offers a balance between penetration depth and sensitivity.

## **1.5 Scattering Parameters (S-Parameters)**

In high-frequency systems, such as RF and microwave biosensors, traditional circuit analysis using voltage and current becomes inadequate due to the complexity of wave behavior. Instead, scattering parameters (S-parameters) are used to describe how electromagnetic waves interact with components and structures. These parameters provide a convenient and powerful way to characterize and simulate the performance of sensors, especially those involving dielectric materials like biological tissues or fluids.

### 1.5.1 Definition and Significance

Scattering parameters represent the relationship between incident and reflected electromagnetic waves at the ports of a network or device. In a two-port network (which is common in biosensor applications), the four primary S-parameters are:

- $S_{11}$  : Input reflection coefficient – measures how much of the incident wave at port 1 is reflected back due to impedance mismatch.
- $S_{21}$  : Forward transmission coefficient – shows how much of the signal from port 1 is transmitted to port 2.
- $S_{12}$  : Reverse transmission coefficient – measures the signal transmission from port 2 to port 1.
- $S_{22}$  : Output reflection coefficient – indicates the reflection at port 2.

These parameters are frequency-dependent and are typically measured in decibels (dB). They are essential for analyzing the resonance behavior, bandwidth, return loss, and insertion loss of RF devices.

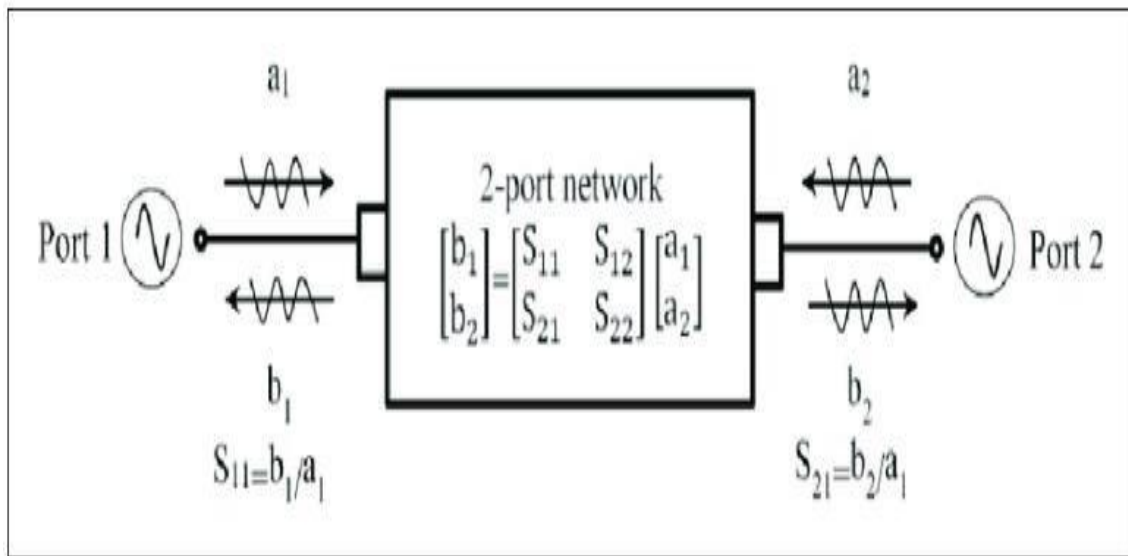
In the context of biosensing, particularly with materials that have frequency-sensitive dielectric properties (like human tissue or glucose-containing solutions), S-parameters help in understanding how the sensor's electromagnetic field is altered by the presence of the target analyte. This makes them especially valuable in non-invasive and label-free biosensing applications.

### 1.5.2 Application of S-Parameters in Sensor Simulation and Design

In biosensor design, S-parameters are used to simulate, evaluate, and optimize the sensor's performance. By modeling how electromagnetic waves propagate through and interact with biological media, engineers can determine how the presence of glucose alters the sensor's response. For instance:

- A change in  $S_{11}$  may indicate that the glucose concentration has altered the impedance of the sensing region.
- A shift in resonant frequency detected via S-parameter curves can be used to quantify glucose levels.

- $S_{21}$  is useful for evaluating signal attenuation or phase shifts, especially in transmission-line based sensors.



*Figure 1.1 Application of S-Parameters in Sensor Simulation and Design*

Simulation tools like CST Studio Suite, HF SIMULATOR (Ansys), or COMSOL Multiphysics are commonly used to compute S-parameters for proposed sensor geometries and materials. These simulations help in:

- Resonator-based sensors: Monitoring shifts in resonant peaks due to dielectric changes.
- Metamaterial-inspired designs: Exploiting engineered structures that are highly sensitive to electromagnetic variations.
- Optimization: Tweaking sensor dimensions, substrate materials, or operating frequency to enhance sensitivity and selectivity.

Moreover, during experimental validation, a Vector Network Analyzer (VNA) is often used to measure S-parameters across a frequency sweep. Comparing these real-world results with simulation data allows for model calibration and performance verification.

## 1.6 Introduction to Metamaterials

### 1.6.1 Definition and Unique Electromagnetic Properties

Metamaterials are artificially engineered structures designed to exhibit electromagnetic properties that are not found in natural materials. Unlike conventional materials, whose electromagnetic behavior is determined by their chemical composition, metamaterials derive their properties from their sub-wavelength structural arrangement. These structures can manipulate electromagnetic waves in unconventional ways, such as bending light "backward" (negative refraction), filtering specific frequencies, or concentrating fields in sub-wavelength regions.

The most notable electromagnetic properties of metamaterials include:

- **Negative permittivity ( $\epsilon$ ) and permeability ( $\mu$ ):** Leading to negative refractive index, which enables exotic phenomena such as reverse Snell's law and cloaking.
- **Resonant behavior:** Metamaterials can be designed to resonate at specific frequencies, making them highly frequency-selective.
- **Enhanced electric or magnetic field localization:** This improves interaction with surrounding media, including biological tissues or fluids.

These unique capabilities allow metamaterials to control and enhance the behavior of electromagnetic fields, making them particularly useful for applications in sensing, imaging, wireless communication, and biomedical diagnostics.

### 1.6.2 Use of Metamaterials in Sensor Sensitivity Enhancement

In the context of biosensing, metamaterials are increasingly being used to enhance sensor sensitivity and selectivity, especially in microwave and terahertz frequency ranges. Their ability to concentrate electromagnetic fields in tiny volumes means that even small changes in the surrounding environment—such as variations in glucose concentration—can lead to measurable shifts in electromagnetic response.

Here are specific ways metamaterials improve sensor performance:

- **Localized field enhancement:** Metamaterials can amplify the local electric or magnetic field in the sensing area, making the sensor more responsive to minute biological changes.
- **Resonant frequency shift:** When the dielectric environment around a metamaterial-based sensor changes (e.g., due to varying glucose levels), the resonant frequency shifts. This shift can be precisely measured using S-parameters.
- **Miniaturization of sensors:** Due to their high field confinement, metamaterial-based sensors can be significantly smaller than traditional sensors while maintaining or improving sensitivity.
- **Multi-band operation:** Metamaterials can be designed to respond to multiple frequencies simultaneously, allowing for multi-analyte detection or enhanced robustness against noise.

Recent studies have demonstrated that split-ring resonators (SRRs), complementary SRRs (CSRRs), and electromagnetically induced transparency (EIT) metamaterials can be integrated into biosensors for non-invasive glucose monitoring. These designs show improved detection limits, better selectivity, and faster response times compared to conventional structures.

**1.7 Conclusion:**

This chapter provided the essential theoretical foundation necessary for understanding the design and simulation of advanced biosensors, particularly those intended for non-invasive blood glucose monitoring. The fundamental principles of electromagnetism serve as the backbone for interpreting how electromagnetic waves interact with biological media. Frequency spectrum analysis highlighted the importance of selecting appropriate RF and microwave bands to achieve optimal penetration, sensitivity, and specificity in glucose detection. The role of scattering parameters (S-parameters) was emphasized as a critical tool in sensor simulation, enabling the quantitative evaluation of sensor performance in both time and frequency domains.

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# ***CHAPTER 2:***

## ***BIOSENSORS***

**2.1. Introduction**

Biosensors are advanced analytical instruments engineered to identify and measure specific chemical or biological entities, referred to as analytes. These devices cleverly combine a biological sensing part with a physicochemical detector, which lets them turn biological responses into signals that can be measured. This integration enables highly specific, sensitive, and rapid detection, rendering biosensors indispensable instruments across various domains, including healthcare, environmental conservation, industrial operations, and food safety.

The main idea behind biosensors is that the biological part and the target analyte only interact with each other. This interaction causes a change that can be seen, and the transducer turns it into an electrical, optical, thermal, or mass-based signal. The growing need for real-time, accurate, and portable analytical tools has pushed the development of biosensor technology.

2.2 Definitions of Biosensors

A biosensor is a new type of analytical device [1] that combines a biological recognition element with a physicochemical transducer. This clever combination makes it possible to find and measure chemical, biological, or physical analytes with great accuracy. A biosensor works by finding a target substance, like an enzyme, antibody, nucleic acid, or even a whole cell, and turning that recognition into a measurable signal. This signal can be electrical, optical, thermal, or any other type of detectable output. Then, this signal is processed and shown to the user so they can understand it. This allows for quick, selective, and very sensitive analysis, often in real time and when it's needed.

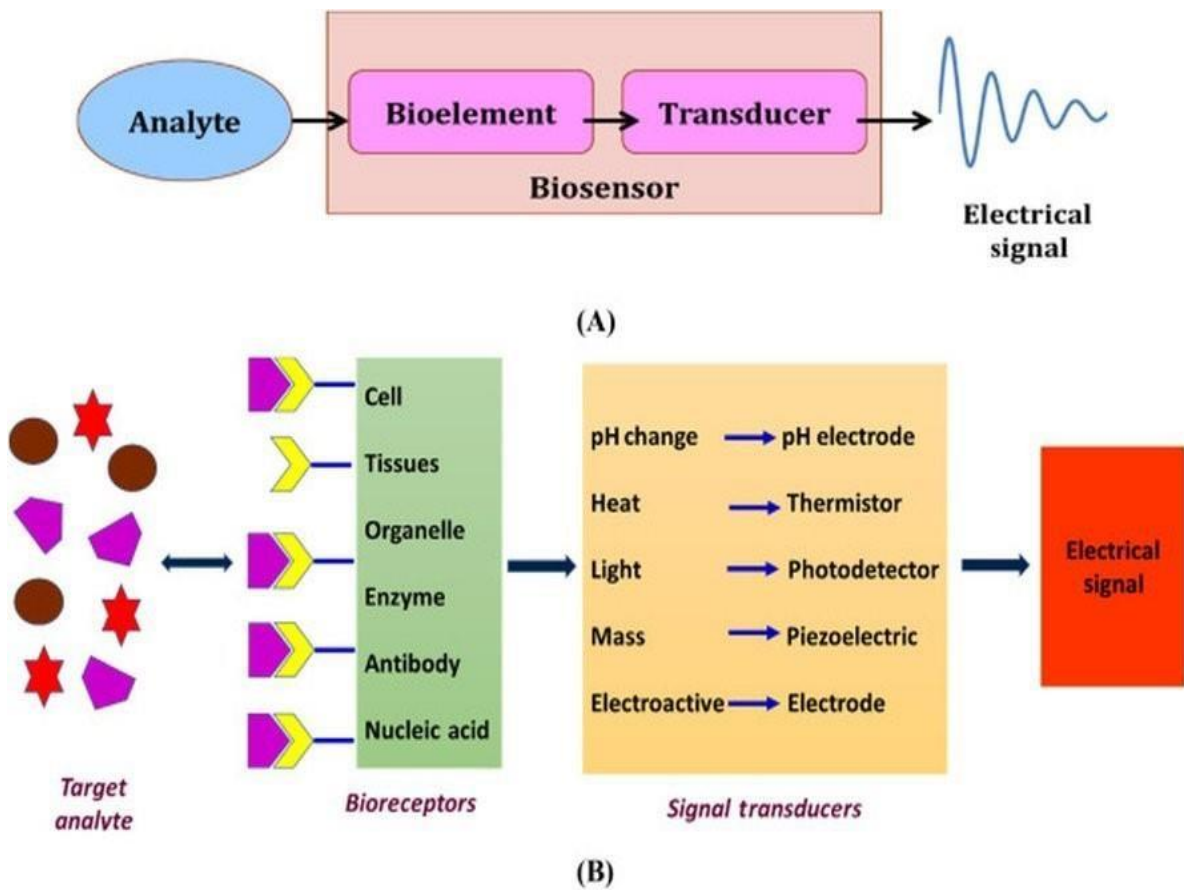


Figure 2.2 Biosensor Components and Signal Transduction

## 2.3 History of Biosensors

Early scientific observations laid the groundwork for the eventual development of biosensors, which started their journey long before the term was even created.

The field has undergone several stages of development, each distinguished by significant breakthroughs and innovations [1][2].

### 1. Early Conceptualizations and Discoveries (Early 20th Century)

- M. Cremer's Observation in 1906: M. Cremer's discovery of a proportionate relationship between the electric potential across a glass membrane and the concentration of an acid in a liquid was the first conceptual precursor to biosensing principles. Understanding how biological interactions could be converted into quantifiable electrical signals was made possible by this ground-breaking work.
- 1916: Protein Immobilization: The first report on the immobilization of protein, specifically invertase, onto activated charcoal was a significant step towards the development of useful biosensors. Because it enables the biological recognition component to be repurposed and incorporated into a stable device, immobilization is essential for biosensors.

### 2. The Birth of Modern Biosensors (1950s-1970s)

- 1956: The Clark Electrode: Often referred to as the "father of biosensors," Dr. Leland C. Clark Jr. created the Clark electrode to measure oxygen quantitatively. By accurately measuring oxygen consumption and electron flow in oxidative phosphorylation, this instrument transformed metabolic research.
- 1962: The First True Biosensor: Building on his oxygen electrode, Clark and Champ Lyons created an amperometric enzyme electrode for blood glucose measurement, which was the first gadget specifically referred to as a biosensor. The modern biosensor officially began with this invention, which used glucose oxidase and showed how biological recognition and electrochemical detection can be combined in real-world applications.
- 1969: The Development of Potentiometric Biosensors The first potentiometric biosensor was presented by Guilbault and Montalvo, who used immobilized urease on an ammonia electrode to detect urea. This increased the number of detection methods
- 1970: The ISFET Revolution: Piet Bergveld created the first BioFET, the ion-sensitive field-effect transistor (ISFET). Applications for highly sensitive and compact

electrochemical and biological sensing were made possible by this tiny semiconductor device.

- Early 1970s: Commercialization Starts: In the early 1970s, Yellow Springs Instruments (YSI) introduced the first commercial glucose biosensor for general public use, opening up this ground-breaking technology for real-world uses, especially in the treatment of diabetes.
3. Expansion and Diversification (1980s-1990s)
    - The commercialization of biosensors grew rapidly in the 1980s, especially in the medical field for the treatment of diabetes. The development of enzyme-based biosensors and immunosensors—which use antibodies for extremely specific detection—were examples of advancements.
    - The 1990s saw a number of important technological advancements that improved sensor sensitivity, made miniaturization easier, and produced new detection methods. In 1993, for example, the LifeScan FastTake blood glucose biosensor was commercialized.
  4. The Nanotechnology and Digital Era (2000s-Present)
    - The incorporation of nanotechnology, which made use of materials like nanotubes, nanocantilevers, nanoparticles, graphene, and quantum dots, signaled a significant change in the 2000s. This greatly enhanced the stability, sensitivity, and miniaturization potential of biosensors.
    - Applications in the biomedical, environmental, and security domains have advanced in the twenty-first century, with ongoing efforts to reduce size, boost specificity, and integrate AI and ML for complex data analysis and better diagnostic precision. With their ability to provide individualized diagnostics and ongoing health monitoring, wearable biosensors and implantable devices have emerged as significant research and commercial interests.

## **2.4 Design and Operational Principles**

A biosensor's effectiveness stems from its carefully engineered design, which typically comprises three main components working in concert to achieve sensitive and specific detection:

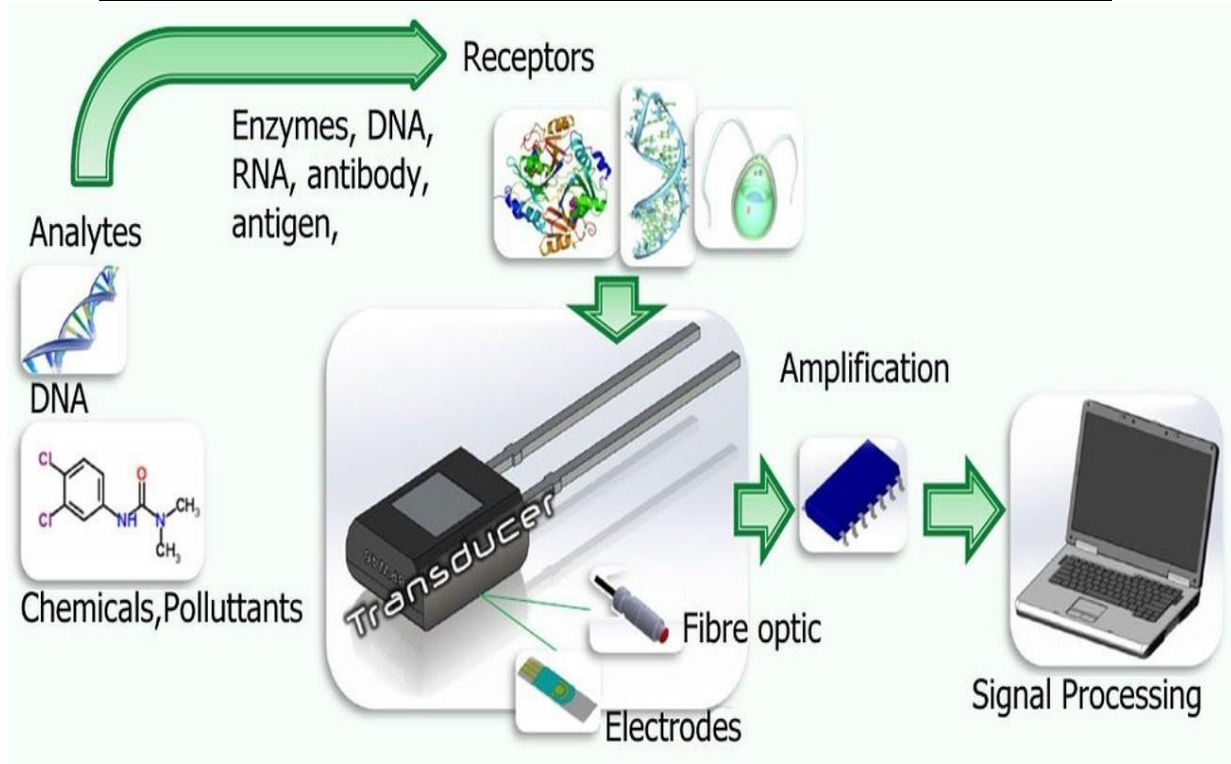


Figure 2.3 An illustrative representation of the fundamental components that constitute a biosensor system.

### 1. Bioreceptor (Biological Recognition Element):

This is the core of the specificity of the biosensor [3]. It is a biological substance or biomimetic element made to interact with the target analyte in a specific way. Common bioreceptors include whole cells, microorganisms, enzymes (such as glucose oxidase for glucose detection), antibodies (for highly specific antigen binding in immunosensors), nucleic acids (for DNA/RNA detection in genosensors), and even synthetic receptors like aptamers. A binding event, catalytic reaction, or conformational change can all occur during the interaction between the bioreceptor and the analyte.

### 2. Transducer: [4]

The crucial component that transforms the biological interaction into a quantifiable physical signal is the transducer. It converts energy into another form, usually an electrical, optical, thermal, or mass-based signal (for example, chemical energy from a reaction, binding energy from a recognition event).

- Electrochemical Transducers: Measure changes in electrical properties such as current (amperometric), potential (potentiometric), or impedance (conductometric) resulting from biochemical reactions.
- Optical Transducers: Detect changes in light properties like absorbance, fluorescence, luminescence, or refractive index (e.g., Surface Plasmon Resonance - SPR) due to the bioreceptor-analyte interaction.
- Mass-based Transducers: Utilize piezoelectric crystals or acoustic wave devices to detect minute changes in mass when the analyte binds to the bioreceptor.
- Thermal (Calorimetric) Transducers: Measure heat changes (either released or absorbed) during exothermic or endothermic biochemical reactions.

### 3. Electronics/Signal Processor and Display:

After receiving the signal from the transducer, this last part amplifies it, processes it (usually converting analog signals to digital), and displays the information in an easy-to-understand format (numerical, graphic, tabular, or image). This guarantees that the results are accurate and comprehensible for the user.

The highly specific interaction between the analyte and the bioreceptor is essential to the operation. The transducer's immediate surroundings undergo a physicochemical change as a result of this interaction, and it transforms this change into a measurable signal. The ultimate objective of biosensor design is to enable quick, easy, and precise measurements—often at the point of care—without requiring a large laboratory setup.

## 2.5 Characteristics of Biosensors

For a biosensor to be effective and widely adopted, it must exhibit several crucial characteristics [5][6] :

- **Specificity**

This refers to the biosensor's ability to selectively detect the target analyte, even in complex sample matrices containing numerous other substances. High specificity minimizes false positives and ensures accurate measurements.

- **Sensitivity**

Sensitivity is the device's capability to detect very low concentrations of the analyte or small changes in its concentration. High sensitivity is crucial for early disease detection or trace pollutant monitoring.

- **Dynamic Range**

This characteristic defines the range of analyte concentrations over which the biosensor can accurately and reliably measure. A wide dynamic range allows for versatility across different sample types and analytical needs.

- **Response Time**

The time it takes for the biosensor to produce a stable and measurable signal after exposure to the analyte is known as its response time. Rapid response times are essential for realtime monitoring and critical diagnostic applications.

- **Stability and Reusability**

Ideally, biosensors should maintain their performance over extended periods without degradation of the biological component and, if possible, be reusable for multiple measurements, thus reducing costs and increasing efficiency.

- **Portability and User-Friendliness**

For widespread adoption, especially in point-of-care settings or field environmental monitoring, biosensors need to be compact, lightweight, and easy to operate without requiring specialized training.

- **Cost-Effectiveness**

The manufacturing and operational costs of biosensors should be economical to facilitate widespread accessibility and commercial viability.

- **Independence from Physical Parameters**

Ideally, the biosensor's performance should not be significantly affected by environmental factors such as temperature, pH, or ionic strength, ensuring consistent and reliable results across varying conditions.

## 2.6 Classification of Biosensors

The type of biological recognition element (bioreceptor) that biosensors use and the transduction mechanism that transforms the biological signal into a measurable output are the two main criteria that are used to classify biosensors. **1. Classification Based on Bioreceptors:**

[7-9]

- **Based on enzymes** Using the high specificity and catalytic activity of enzymes, biosensors are one of the most widely used types. The transducer detects a change (such as a pH shift, oxygen consumption, or product formation) that results from a reaction that the enzyme catalyzes involving the analyte. One excellent example is glucose biosensors that use glucose oxidase.
- **Immunosensors:** The extremely specific binding affinity that exists between antibodies and antigens is utilized by these biosensors. A detectable signal is produced when an antibody that has been immobilized on the sensor surface attaches itself to its target antigen in the sample. They are frequently utilized in biomarker and infectious disease diagnostic testing.
- **DNA/Genosensors:** These use strands of DNA or RNA as bioreceptors. Through hybridization events, in which a complementary DNA/RNA strand from the sample binds to the immobilized probe, they are able to identify particular genetic sequences. Applications include forensic analysis, genetic disease screening, and pathogen detection.
- **Microbial Biosensors:** These use microorganisms, tissues, or entire cells as the bioreceptor. When the analyte is present, these biological entities' metabolic activity

changes, resulting in a detectable signal. They are frequently employed for fermentation process control or environmental monitoring.

- Aptasensors: These are a newer class that uses aptamers, which are synthetic nucleic acid ligands (DNA or RNA molecules) or peptides. Aptamers can bind to specific target molecules with high affinity and selectivity, mimicking the function of antibodies but offering advantages in terms of synthesis, stability, and ease of modification.

### **2.6.1 Classification Based on Transducers:**

-Electrochemical Biosensors [10-12]:

- Amperometric Biosensors: Measure changes in current resulting from electron transfer reactions during the bioreceptor-analyte interaction.
- Potentiometric biosensors: These devices measure variations in the electrode surface potential (voltage) brought on by shifts in the distribution of charges or ion concentration.

One well-known example is Ion-Sensitive Field-Effect Transistors (ISFETs).

- Conductometric Biosensors: Track variations in the solution's electrical conductivity or resistance brought on by the biochemical reaction.
- Electrochemical stimuli are used to generate light signals in electrochemiluminescence (ECL) biosensors, which have a low background noise and high sensitivity.
- Optical Biosensors: These detect changes in light properties.
- Fluorescence-based: Track variations in wavelength or fluorescence intensity as a result of analyte binding.
- Luminescence-based: Identify light released when a biochemical reaction takes place.
- Plasmon resonance on the surface (SPR) Biosensors: Provide label-free detection by measuring variations in refractive index close to a metal surface when molecules attach to it.
- Mass-based Biosensors:
  - Piezoelectric Biosensors: Make use of piezoelectric crystals that vibrate at a particular frequency, such as the Quartz Crystal Microbalance, or QCM. Its resonant frequency changes when mass attaches to the crystal surface, giving an indication of the bound mass.

- Similar to piezoelectric sensors, acoustic wave biosensors identify variations in the properties of acoustic wave propagation.
- Thermometric (calorimetric) biosensors measure the amount of heat produced or absorbed during biochemical reactions in relation to the concentration of the analyte.
- Physical Biosensors: These biosensors are less frequently used for chemical detection, but they can be classified based on how they react to physical stimuli. For example, they can be used to study neurological responses like touch or hearing.

## **2.7 State of Biosensor Technology**

Rapid developments in the field of biosensors [13-16], which integrate materials science, biotechnology, and artificial intelligence, are the result of interdisciplinary research. Enhancing sensitivity, selectivity, miniaturization, and the capacity to conduct multiplexed and real-time analysis are the main goals.

- Biosensors Driven by Nanotechnology: It is crucial to use nanomaterials like graphene, carbon nanotubes, gold and silver nanoparticles, and quantum dots. The sensitivity, detection limits, and multiplexing capabilities of biosensors are improved by these materials, which also have outstanding electrical and optical qualities and superior surface-to-volume ratios. Sensor design is being revolutionized by bio-fabrication techniques that use these nanomaterials through contact or non-contact patterning, frequently with polymer coatings
- Wearable and Implantable Biosensors: This is a burgeoning area, offering continuous, real-time monitoring of various biomarkers. Wearable devices, from smartwatches and smart patches to percutaneous sensors, track physiological signals like glucose levels, lactate, stress hormones, electrolytes, and cardiac markers. Implantable biosensors are being developed for long-term monitoring, though challenges in biocompatibility and reliability remain active research areas.

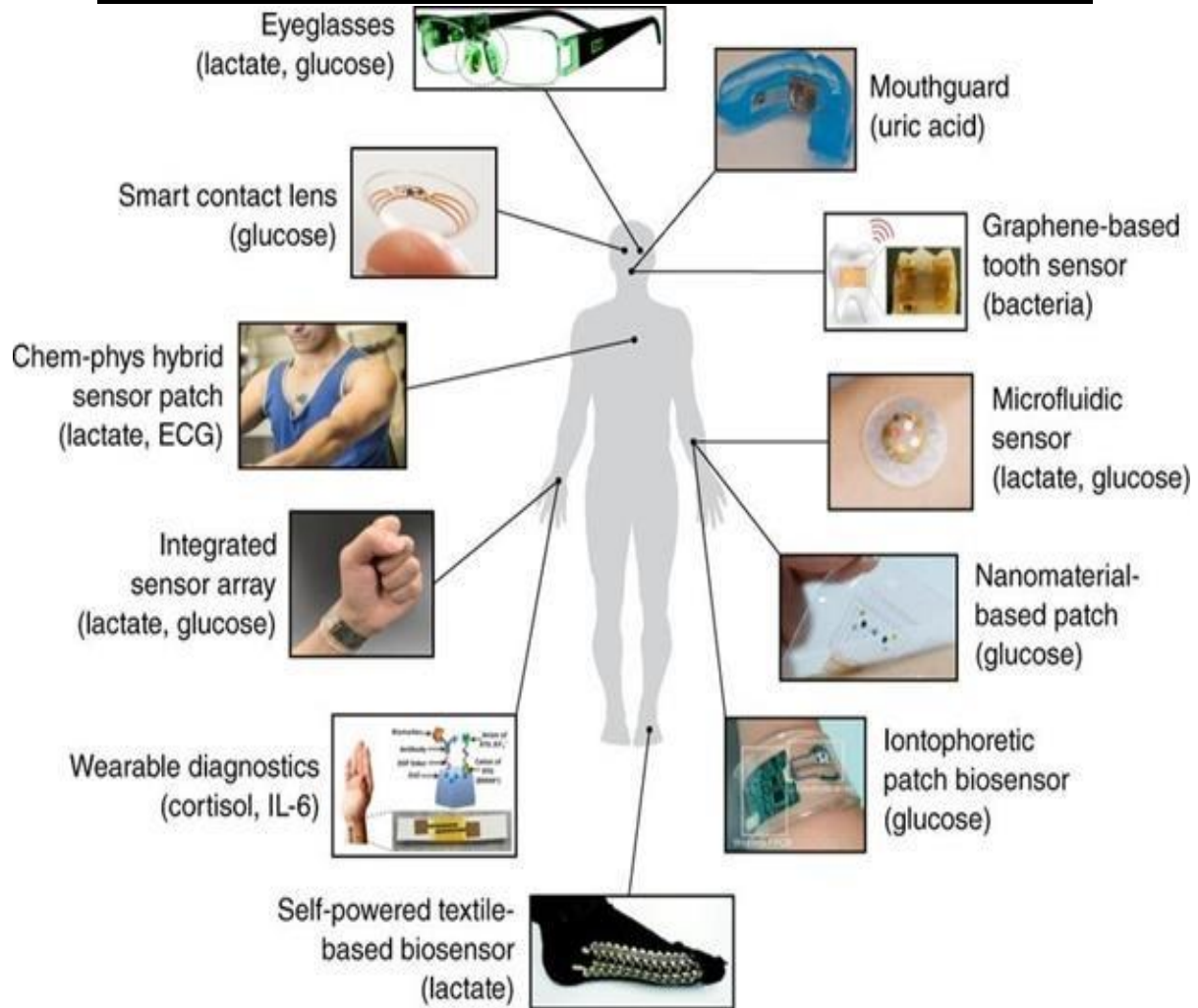


Figure 2.4 An illustration of wearable biosensors used for healthcare monitoring.

- **Advanced Electrochemical Biosensors:** Because of their affordability, ease of use, and quick reaction, these continue to be the most popular. Miniaturized formats for point-of-care testing, improved electrode materials, and microfluidics for sample handling are examples of innovations.
- **Advanced Optical Biosensors:** These sensors provide extremely sensitive detection for environmental monitoring and clinical diagnostics by utilizing photonic and plasmonic effects. At the forefront of these developments are methods such as electrochemiluminescence and Surface Plasmon Resonance (SPR).
- **Integration of Artificial Intelligence (AI) and Machine Learning (ML):** Biosensor systems are increasingly incorporating AI and ML algorithms. Complex data analysis, pattern recognition, noise reduction, and enhancing diagnostic accuracy—particularly in

multianalyte sensors—are among their uses. For example, Bayesian algorithms are being used in clinical trials to incorporate prior knowledge and improve the accuracy of biosensor data.

- **Devices for Point-of-Care Testing (POCT):** Rapid, on-site testing for a variety of illnesses, such as infectious diseases (like COVID-19 and HIV), cancer biomarkers, and cardiovascular markers, is made possible by the development of portable, miniature biosensors. These tools are essential for rapid diagnostics in remote or resource-constrained environments.
- **Aptamer-Based Biosensors and Molecularly Imprinted Polymer (MIP) Biosensors:** These artificial receptors provide better robustness, stability, and selectivity than conventional biological recognition components. MIPs, which provide targeted detection, are moving toward wearable applications.
- **Biological Field-Effect Transistors, or BioFETs:** BioFETs, which are constantly developing, use direct electrical transduction to provide nanoscale sensitivity for uses ranging from DNA detection to ion sensing.
- **Multiplexed Biosensors:** The capacity to detect several analytes at once is a noteworthy trend. This improves the thoroughness and effectiveness of diagnostics, especially in complex biological samples..

## **2.8 Applications of Biosensors**

Biosensors have permeated numerous sectors, offering rapid, sensitive, and specific detection capabilities that are transforming how we diagnose diseases, monitor environments, ensure food safety, and even interact with technology.

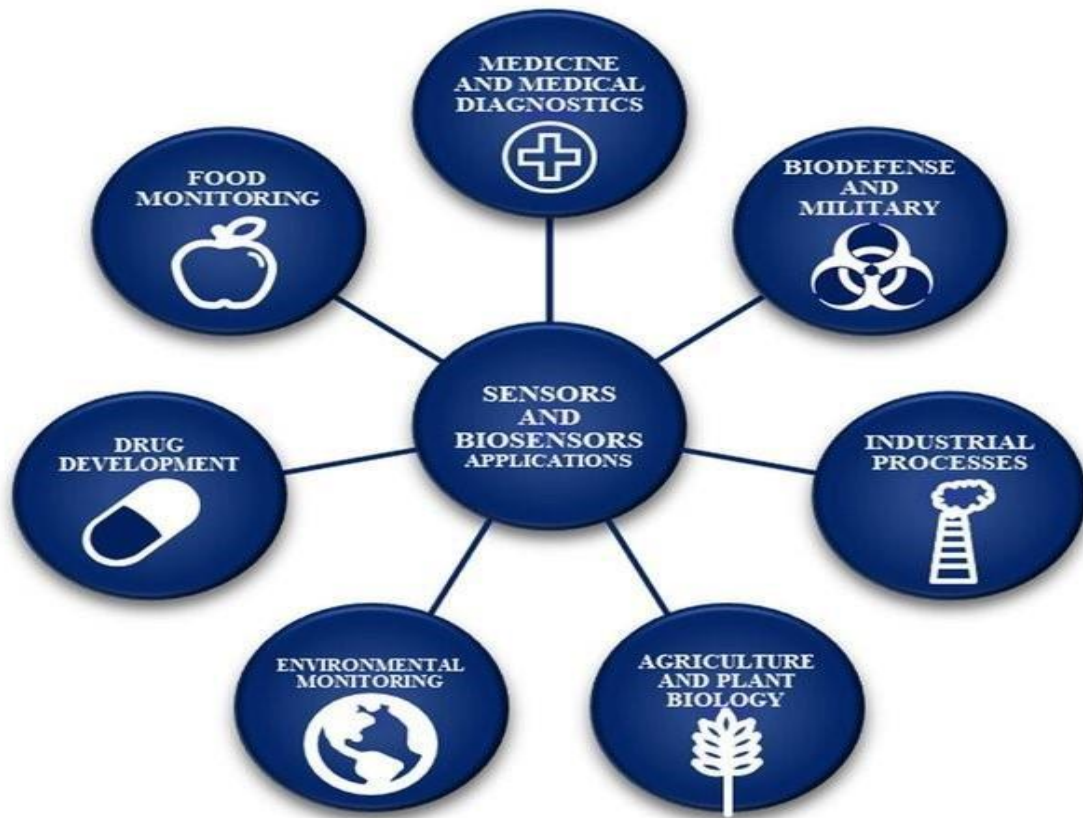


Figure 2.5 Visual representation of the broad and impactful applications of biosensors across various industries.

### 1. Healthcare and Clinical Diagnostics [17]

This is arguably the most impactful application area for biosensors. They are indispensable for:

- **Glucose Monitoring:** The most popular use, glucometers help millions of diabetics control their blood sugar levels every day. This is being advanced further by Continuous Glucose Monitors (CGMs), which provide non-invasive, real-time readings.

- Disease Diagnosis and Monitoring: prompt and precise identification of genetic disorders, chronic illnesses (such as heart disease, cancer markers like troponins), and infectious diseases (such as HPV, HIV, COVID-19, and influenza). They support individualized treatment plans and early intervention.
- Clinical Analysis: Measurements of blood gases (pO<sub>2</sub>, pCO<sub>2</sub>), lactate, cholesterol, uric acid, and other metabolites are made for a thorough evaluation of the patient.
- Drug discovery and development includes high-throughput screening of potential drugs, real-time pharmacokinetic profile tracking, drug efficacy monitoring, and the identification of new drug targets.
- Wearable Health Devices: Integrated into smartwatches, patches, and other wearables, these devices allow for proactive health management by continuously monitoring physiological signals, health indicators, and vital signs (heart rate, oxygen saturation).
- Point-of-Care Testing (POCT): This technology makes it possible to perform quick, on-site diagnostics outside of conventional laboratory settings, which is essential in emergency medicine, remote locations, and settings with limited resources.

## 2. Environmental Monitoring [18-19]

Biosensors play a critical role in safeguarding environmental health:

- Pollutant Detection: Identifying heavy metals, pesticides, industrial chemicals, and toxins in water, air, and soil. This helps assess environmental quality and prevent contamination.
- Gas Detection: Monitoring greenhouse gases, toxic gases, and other atmospheric pollutants.
- Biological Contaminants: Detecting pathogens and other biological agents in ecosystems to prevent outbreaks and ecological damage.

## 3. Food Industry and Safety [20]

Ensuring the quality and safety of consumables:

- 
- **Quality Control:** Monitoring fermentation products, amino acids, carbohydrates, alcohols, and other parameters to ensure product quality and authenticity (e.g., in wine, juices).  
**Pathogen and Toxin Detection:** Rapidly identifying bacteria, viruses, and microbial toxins in food products to prevent foodborne illnesses.
- **Allergen Detection:** Identifying common food allergens to protect consumers with sensitivities.
- **Pesticide Residue Detection:** Ensuring food products are free from harmful pesticide levels.

### 2. Defense and Security[21]

Biosensors are vital tools for national security and public safety:

- **Biological and Chemical Agent Detection:** Rapidly identifying biological warfare agents, hazardous chemical substances, and explosives in the field.
- **Threat Identification:** Enabling quick response to potential threats through portable, deployable biosensor systems.

### 3. Agriculture and Veterinary Applications [22]

Improving crop yields and animal health:

- **Soil Analysis:** Monitoring soil nutrients, pH levels, and pesticide residues to optimize crop growth.
- **Plant Health Diagnostics:** Detecting plant pathogens, stress hormones, and nutritional deficiencies for proactive agricultural management.
- **Animal Health:** Diagnosing diseases in livestock and companion animals, monitoring metabolic processes, and detecting pathogens.

### 4. Industrial Biotechnology and Bioprocess Control [23]

Optimizing industrial processes:

- 
- Bioreactor Monitoring: Real-time monitoring of metabolites, enzyme activity, and process parameters in bioreactors to optimize fermentation and other biotechnological production processes.  
Process Control: Ensuring efficient and consistent production in various industrial applications.

Biosensors are also integrating into novel interactive systems, such as "biometric painting," where real-time biosensor data representing emotional states are used to create visual art, blurring the lines between science and art. Furthermore, the future holds promise for their integration into electronic paper, morphing devices, and smart contact lenses.

## **2.9 Conclusion:**

With their accurate, quick, and sensitive analytical capabilities, biosensors are a remarkable example of biology and engineering coming together to revolutionize a variety of fields. From their early origins in basic electrochemical observations made by individuals such as M. Cremer and the groundbreaking research of Leland C. Clark, these devices have developed into highly advanced tools that are essential to contemporary analytical science.

The trend toward personalized medicine and proactive environmental stewardship will be fueled by these developments, which promise even more compact, intelligent, and easily accessible analytical solutions.

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# ***CHAPTER 3:***

## *SIMULATION AND DISCUSSION*



### 3.1. Introduction

In this chapter, we explore the design and simulation of a metamaterial-based biosensor for the detection of blood glucose concentration through electromagnetic analysis. The proposed structure features a resonator engineered using a split-ring configuration, precisely optimized to detect shifts in the reflection coefficient ( $S_{11}$ ) resulting from changes in the dielectric properties of biological fluids. This approach leverages the high sensitivity of metamaterial (MTM) structures to electromagnetic perturbations, enabling the accurate detection of varying glucose concentrations in blood samples.

This section presents the structural design, dimensional characteristics, and material specifications of the proposed -shaped biosensor based on a metamaterial-inspired **rectangular resonator (RR)**. The sensor is engineered to detect variations in blood glucose concentration by monitoring the electromagnetic behavior—specifically the shift in resonant frequency and change in reflection coefficient ( $S_{11}$ )—caused by the dielectric properties of the test fluid.

### 3.2. Designs and Dimensions :

The resonator is carefully modeled using advanced electromagnetic simulation software, allowing for in-depth analysis of field distribution, resonant frequency behavior, and sensitivity under different glucose levels and sample volumes. Through this simulation environment.

#### 3.2.1 Structural Overview

The biosensor is built on a conventional microstrip planar configuration, consisting of a metal-dielectric-metal layout. The top copper layer is patterned to form a **rectangular resonator** (Figure 3.1), while the bottom layer serves as a continuous ground plane.

The resonator operates at a target frequency of 3.5 GHz, chosen for its suitability within the ISM band and its sensitivity to dielectric variations in biological samples. The excitation is performed via two symmetrical microstrip feed lines, directly coupled to the resonant structure.

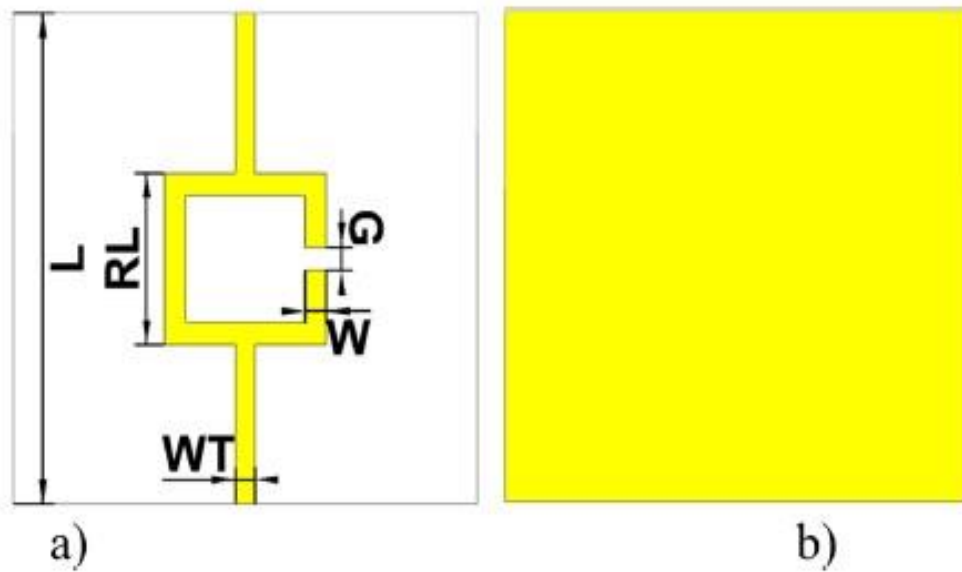


Figure 3.1 Proposed microstrip square ring resonator. a Top view and b bottom view .

### 3.2.2 Substrate and Material Selection

To ensure low loss and high sensitivity, the sensor is designed on **Rogers RT/Duroid 5880**, which offers superior RF performance and is commonly used in medical sensing applications.

These characteristics Table 3.1 minimize signal attenuation and ensure high Q-factor resonances, vital for precise glucose detection

Table 3.1 characteristics of biosensor

PARAMETER	VALUES
Substrate material	Rogers RT5880
Relative permittivity ( $\epsilon_r$ )	2,2
Loss tangent ( $\tan \delta$ )	0.0009
Substrate thickness (h)	1.47mm
Copper thickness (t)	0.035mm

### 3.2.3 Rectangular Ring Geometry and Feed Design

The resonator consists of a single rectangular ring structure (*Figure 3.2*) etched into the top copper layer of the substrate, incorporating a narrow split gap that enhances capacitive behavior and concentrates the electric field in the sensing region.

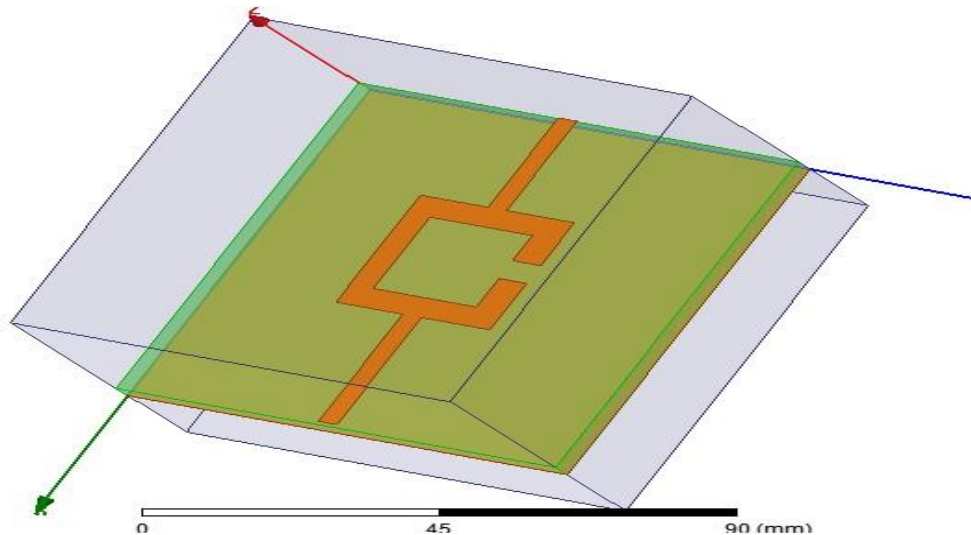


Figure 3.2 Proposed biosensor without sample

This configuration allows strong electromagnetic interaction with the sample *Figure 3.3* placed directly over the gap, which is the most sensitive area of the structure. The dimensions of the rectangular rings *Table 3.2*, including length, width, and gap size, are carefully optimized to maximize the sensitivity and ensure a clear shift in the resonant frequency in response to variations in the dielectric properties of the blood sample.

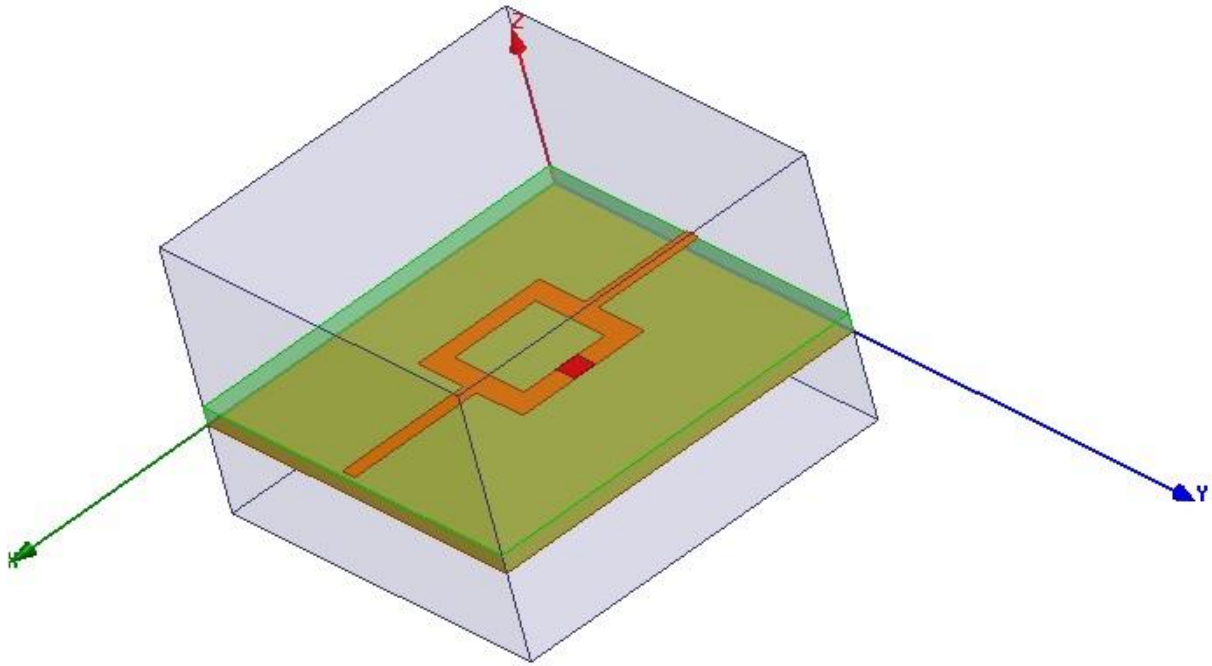


Figure 3.3 Proposed biosensor with sample

- **Top Layer:** rectangular ring resonator etched on copper
- **Substrate:** Rogers RT5880,  $\epsilon_r = 2.2$ ,  $h = 1.47$  mm
- **Bottom Layer:** Continuous copper ground plane
- **Connector Interface:** 50-ohm SMA ports

The **gap region** of the square ring—acting as the active sensing area—was left exposed and accessible to apply the blood samples Figure 3.1.

Table 3.2 Dimensions of biosensor

PARAMETER	VALUES( mm)
L	85.71
RL	30
WT	3.65

G	4
h	1.47

The **split gap in the rectangular resonator** acts as the most sensitive region due to the presence of strong localized electric fields, which enhance the interaction with the material under test. A **semi-rectangular feed connection** is implemented to maintain symmetry and facilitate efficient impedance matching. The **feed line width** is precisely calculated to achieve a **50  $\Omega$  characteristic impedance**, ensuring minimal signal reflection and optimal power transfer between the feed line and the resonator structure.

### 3.2.4 Sample Placement and Sensing Region

The blood or glucose solution is introduced in the region immediately above the **split gap** of the square ring. This is where the electric field is most concentrated, making it the ideal sensing zone.

- **Sample thickness:** 0.5 mm
- **Sensing zone:** 10 mm centered over the SRR gap
- **Permittivity range:**  $\epsilon_r = 50\text{--}58$  depending on glucose concentration

As the dielectric constant of the sample changes, the **effective permittivity** seen by the resonator shifts, resulting in a measurable **frequency shift** in the resonant behavior.

## 3.3 Electromagnetic Modeling and Debye Characterization

To accurately simulate the frequency-dependent behavior of the biological fluid, the **Debye model** is employed for the permittivity of blood.

This allows realistic modeling of the dispersive and loss characteristics of glucose solutions.

The complex permittivity is modeled as:

$$\varepsilon^*(\omega) = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + j\omega\tau} \quad (3.1)$$

Where:

- $\varepsilon^*(\omega)$  is the frequency-dependent complex permittivity,
- $\varepsilon_s$  and  $\varepsilon_{\infty}$  are the static and infinite-frequency permittivities,
- $\tau$  is the relaxation time constant,
- $\omega$  is the angular frequency.

This model is integrated into HF simulator Suite simulations to analyze how changes in glucose concentration alter the resonator's performance.

$$\varepsilon_{\infty}(G) = 5.38 + G \times 30 \times 10 \quad (3.2)$$

$$\varepsilon_s(G) = 80.68 + G \times 0.207 \times 10 \quad (3.3)$$

$$\tau(G) = 9.68 + G \times 0.23 \times 10 \quad (3.4)$$

Where

G is the glucose concentration in milligrams per deciliter (mg/dl).

The blood's dispersive characteristics as a function of glucose content are modeled for glucose concentrations of 80, 100, 120, and 140 mg/dl.

The results are then fitted to the single-pole Debye empirical model in Suite software for sensor simulations to evaluate their performance.

### 3.4 Simulation Configuration

The entire structure is simulated using **HF simulator** over a frequency sweep from **1 GHz to 5 GHz**. The excitation is applied via **two waveguide ports** positioned at the ends of the microstrip feed lines.

#### Boundary Conditions:

- **PEC (Perfect Electric Conductor)**: For the copper resonator and ground plane
- **Waveguide Ports**: For measuring reflection coefficient (S11)

The simulation outputs the **S-parameters**, allowing the tracking of resonant frequency shifts caused by different glucose concentrations.

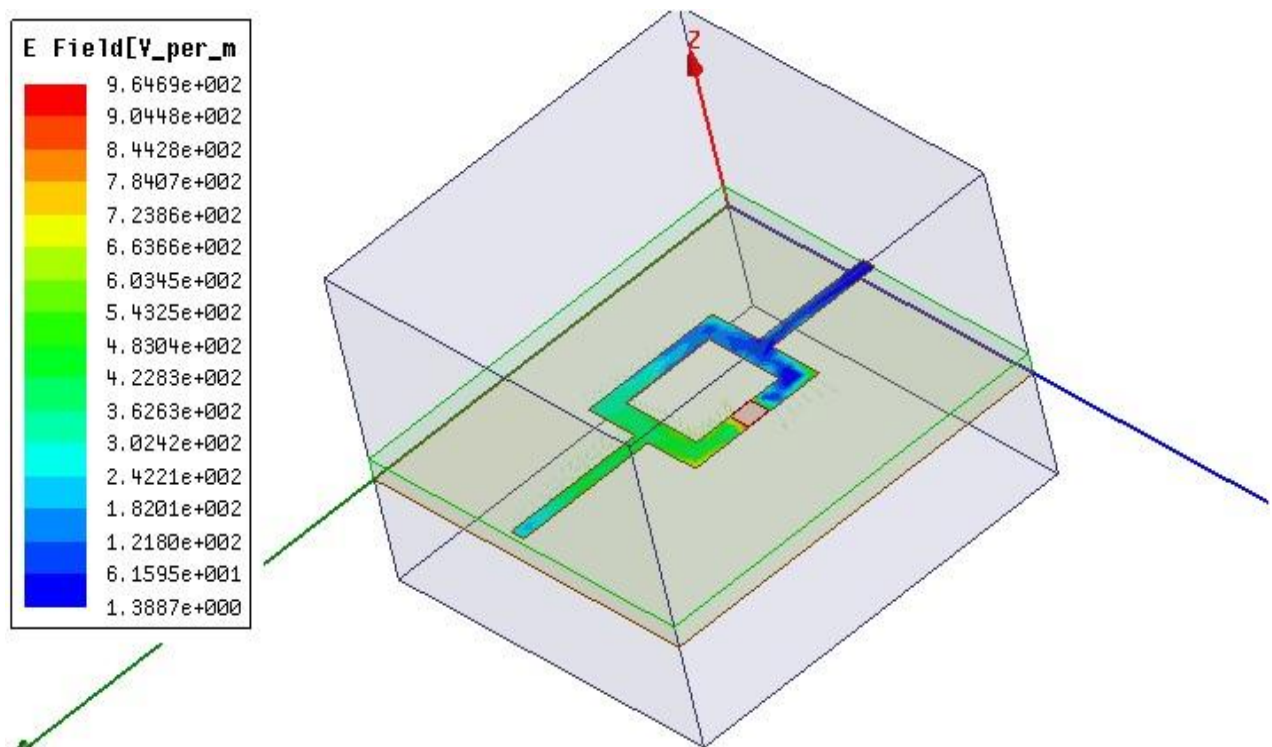


Figure 3.4 Simulation of the proposed biosensor (E field v/m ).

### 3.4.1 Simulated S-Parameters

The proposed biosensor operates on the principle of **capacitive-inductive resonance**, where the metal ring induces inductance ( $L_0$ ) and the gap provides effective capacitance ( $C_a$ ). The resonance frequency can be approximated using the expression:

$$f = \frac{1}{\sqrt{L_0 C_0}} \quad (3.5)$$

The **reflection coefficient (S11)** obtained through simulation Figure 3.5. The biosensor exhibits a resonance around **3.508 GHz**

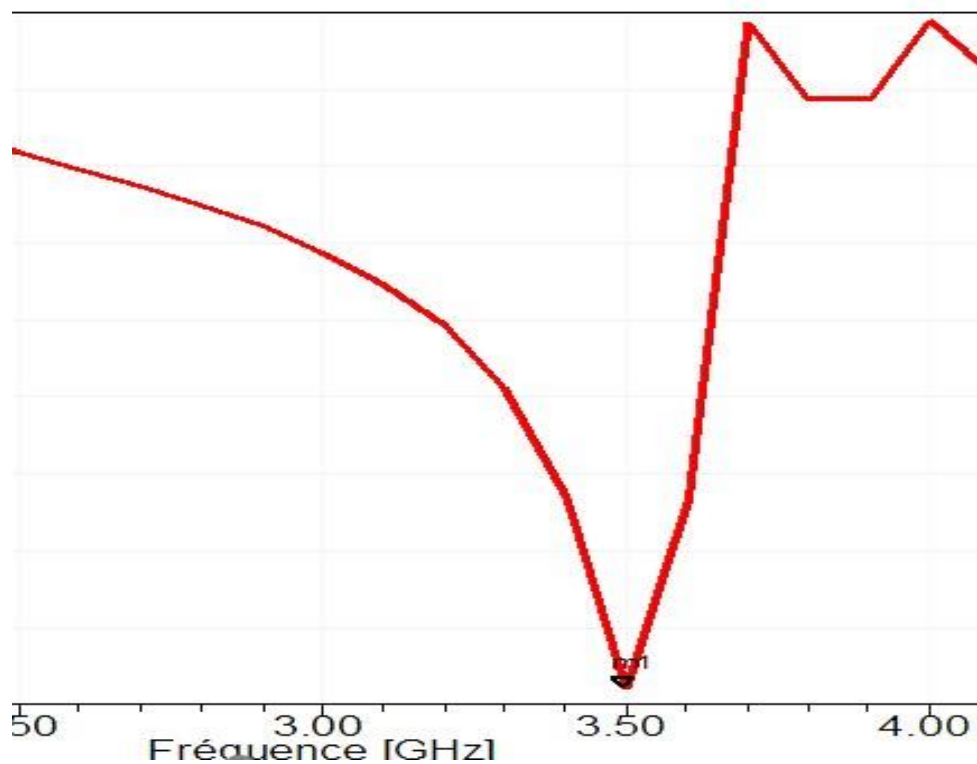


Figure 3.5 The reflection coefficient (S11) of the proposed structure without sample

### **3.4.2 Correlation Between Glucose Concentration, Resonance Shift**

The glucose concentrations measured using the **glucometer device** were found to be in close agreement with the values assumed during the simulation phase. Once the blood samples were acquired and tested, they were carefully introduced into the **Square resonator's sensing gap** , and the **S11 response** was recorded using the Vector Network Analyzer (VNA).

#### **3.4.2.1 Setup for Electromagnetic Simulation**

The simulation was conducted using **HF simulator**, to observe the resonance shift over the frequency band of **1 to 5 GHz**. A constant glucose concentration level was changed from 40 ml/dl to 200ml/dl.

- The **blood sample** was modeled using the **Debye dielectric model**, with appropriate parameters for human blood.
- The **sensor geometry** remained unchanged throughout the test; only the dielectric sample layer thickness was varied.
- Ports were placed at the ends of the microstrip feed lines, and S-parameters were extracted after full-wave simulation.

#### **3.4.2.2 Comparative Analysis**

- ❖ The graph shows the **S11 parameter** in dB over the frequency range **1 GHz to 5 GHz**, simulated for the biosensor with blood containing **140 mg/dL glucose**.

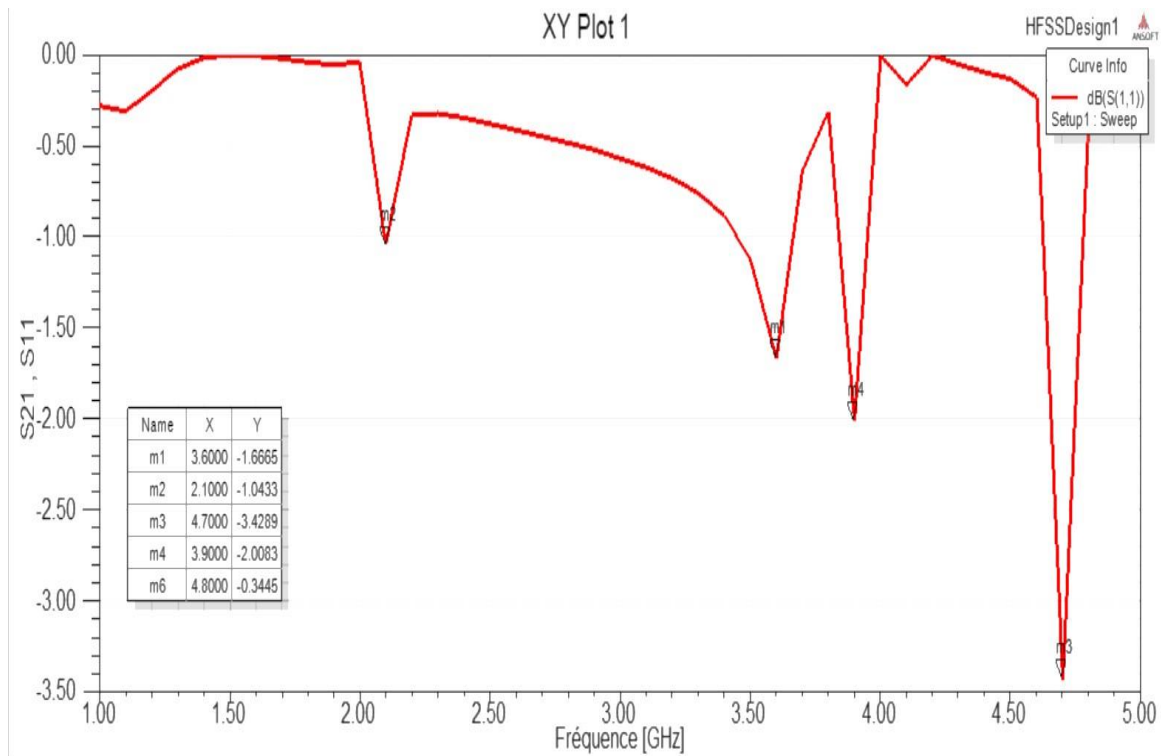


Figure 3.6 The Reflection coefficient (S11) of the proposed structure blood containing **140 mg/dL** glucose

### Observations :

- Multiple Resonant Frequencies** are observed, corresponding to sharp dips in the S11 curve:

  - **m1 (3.6 GHz)** with S11  $\approx$  -1.67 dB ○ **m3 (4.7 GHz)**
  - with S11  $\approx$  -3.43 dB  $\rightarrow$  strongest resonance** ○ **m4 (3.9 GHz)**
  - with S11  $\approx$  -2.01 dB**
- The **deepest resonance** occurs at **4.7 GHz**, which may correspond to a strong interaction between the sensor and the blood's dielectric properties at 140 mg/dL glucose.

3. The **resonance at 3.6 GHz** (m1) remains close to the **target design frequency** (3.5 GHz), indicating that the glucose concentration of 140 mg/dL still induces a resonant behavior near the biosensor's optimal sensitivity range.

❖ The graph shows the **S11 parameter** in dB over the frequency range **1 GHz to 5 GHz**, simulated using HF for the biosensor with blood containing **100 mg/dL glucose**.

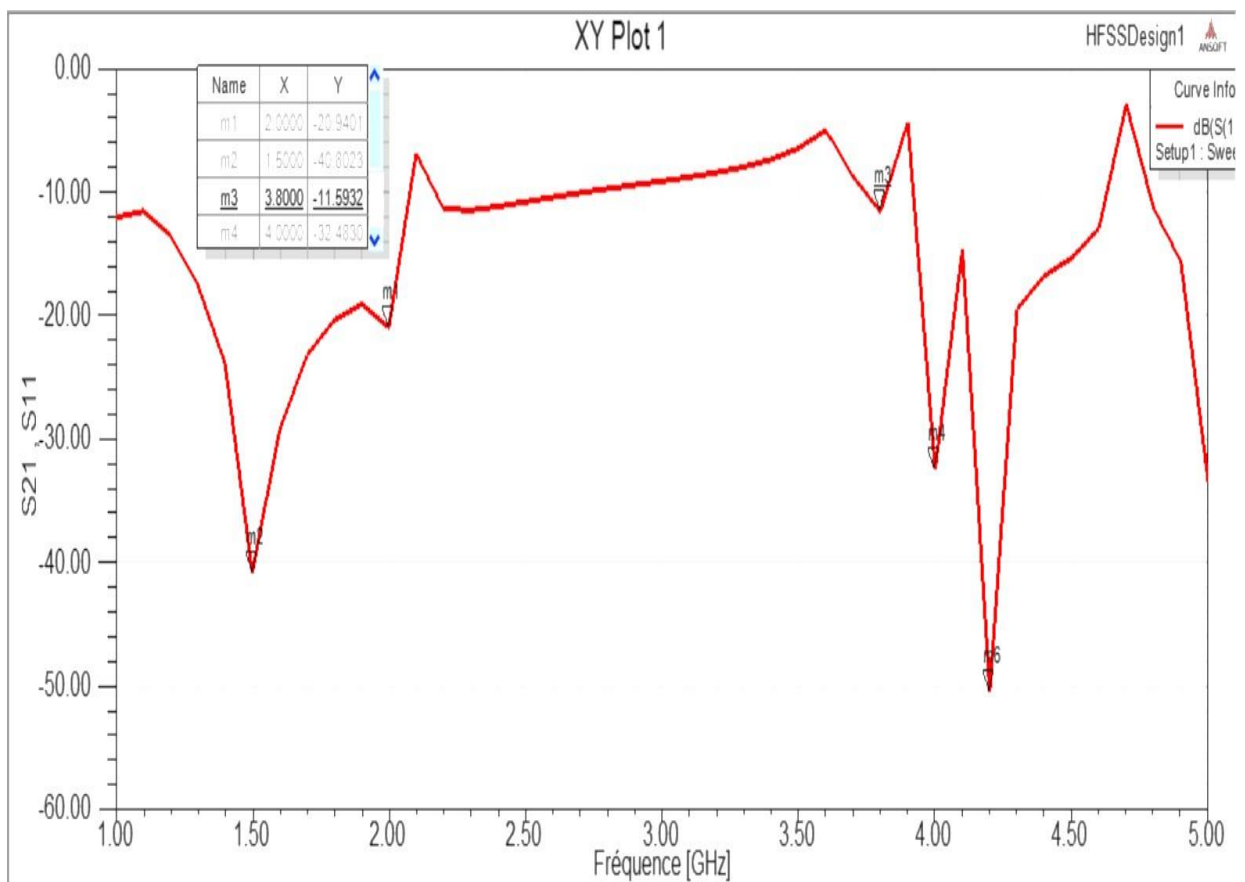


Figure 3.7 The Reflection coefficient (S11) of the proposed structure blood containing **100 mg/dL** glucose.

#### Observations:

Multiple **resonant frequencies** are observed, corresponding to sharp dips in the S11 curve:

- **m1 (2.00 GHz) with S11  $\approx$  -20.94 dB**
- **m5 (4.20 GHz) with S11  $\approx$  -50.80 dB  $\rightarrow$  strongest resonance**
- **m2 (1.5 GHz) with S11  $\approx$  -40.80 dB**
- **m4 (4.00 GHz) with S11  $\approx$  -32.48 dB**

The **deepest resonance** is observed at **4.20 GHz (m2)** with an S11 of approximately **-50.80 dB**, indicating a **highly efficient energy absorption** and strong interaction between the sensor and the dielectric properties of the blood sample at **100 mg/dL glucose**.

Additional notable resonances at **2.00 GHz** and **4.00 GHz** suggest **multi-band sensing behavior**, which enhances detection flexibility and sensitivity.

The **very low S11 values** in this simulation indicate **excellent impedance matching** and strong sensor response under this glucose condition.

- ❖ The graph shows the **S11 parameter** in dB over the frequency range **1 GHz to 5 GHz**, simulated using HF for the biosensor with blood containing **50 mg/dL glucose**

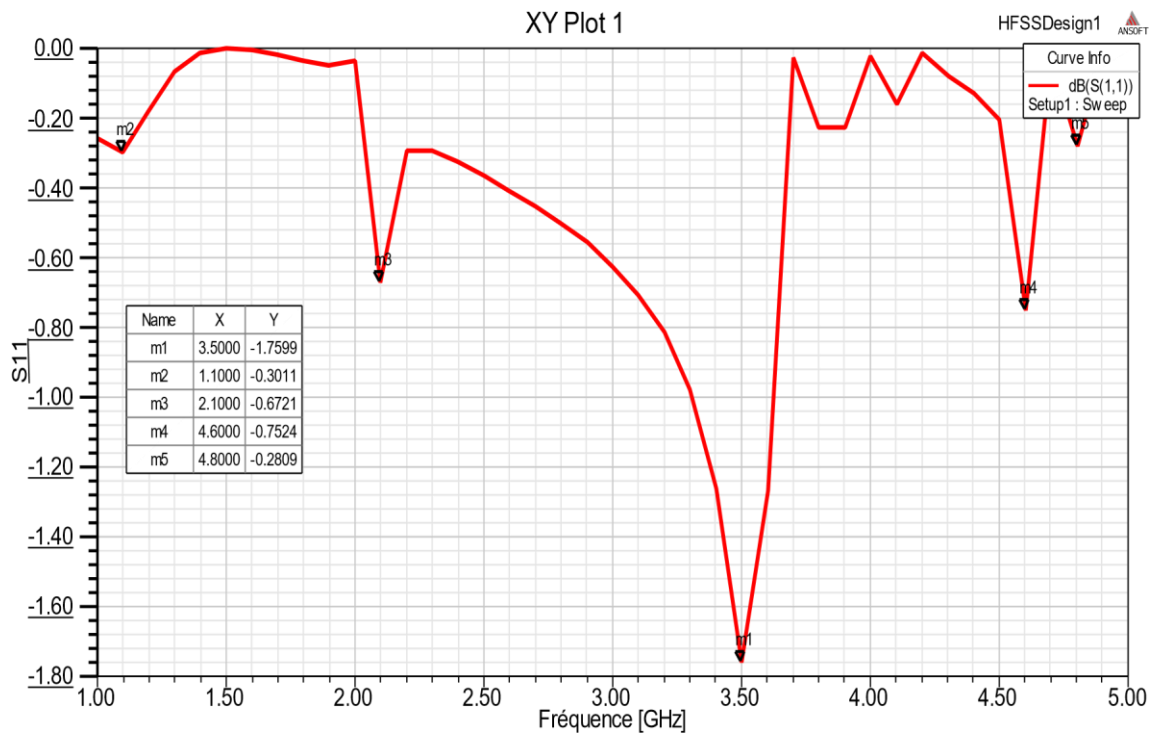


Figure 3.8 The Reflection coefficient (S11) of the proposed structure blood containing **50 mg/dL** glucose.

### Observations 3 :

Several **resonant frequencies** are observed as dips in the S11 curve:

- **m1 (3.5 GHz) with S11  $\approx$  -1.76 Db  $\rightarrow$  strongest resonance**
- **m2 (1.1 GHz) with S11  $\approx$  -0.30 dB**
- **m3 (2.1 GHz) with S11  $\approx$  -0.67 dB**
- **m4 (4.6 GHz) with S11  $\approx$  -0.75 dB**
- **m5 (4.8 GHz) with S11  $\approx$  -0.28 dB**

Among these, the most prominent resonance is observed at **3.5 GHz (m1)**, which closely matches the **sensor's design frequency**, suggesting that **50 mg/dL glucose** induces only a slight dielectric disturbance, maintaining resonance at the expected frequency.

The **S11 values remain above -2 dB**, indicating **weaker coupling and lower absorption**, compared to higher glucose concentrations. This is consistent with the expectation that **lower glucose levels correspond to smaller shifts in the dielectric constant**, and therefore **reduced resonant response**.

### Comparison:

- At **50 mg/dL**, the sensor response is weak. The **S11 values are shallow**, with resonance barely reaching below -2 dB. This implies **poor detection accuracy** for low glucose levels unless the structure is further optimized (e.g., enhancing the electric field in the gap region).
- At **100 mg/dL**, the sensor exhibits **excellent performance**, with an **S11 dip of -40.8 dB at 1.5 GHz**. This is a clear indication of **strong electromagnetic coupling** and high interaction with the dielectric properties of the blood.

- At **120 mg/dL**, the sensor still performs well with a **moderate S11 dip of -3.43 dB** at **4.7 GHz**. Although not as deep as at 100 mg/dL, the frequency shift is significant and measurable, validating the sensor's capability to **track increasing glucose concentrations**.

The simulation results demonstrate that the biosensor is most sensitive around **100 mg/dL**, showing a very strong and sharp resonance. For **higher or lower concentrations**, the response is still detectable, but the **resonance becomes less pronounced**.

This proves the feasibility of using this SRR-based sensor to **monitor glucose levels** through **frequency shift and S11 magnitude**—with potential for calibration to cover a broader range accurately.

### 3.4.3 Simulation Result – Thickness = 0.035 mm

- **Resonance frequency:** Approximately **3.48 GHz**
- **Reflection coefficient (|S11|):** Relatively **higher frequency, shallower dip**
- **Interpretation:** The thin dielectric layer imposes **minimal perturbation** on the electromagnetic field, resulting in a **weaker interaction** and **higher resonance frequency**. This condition represents the sensor's baseline.

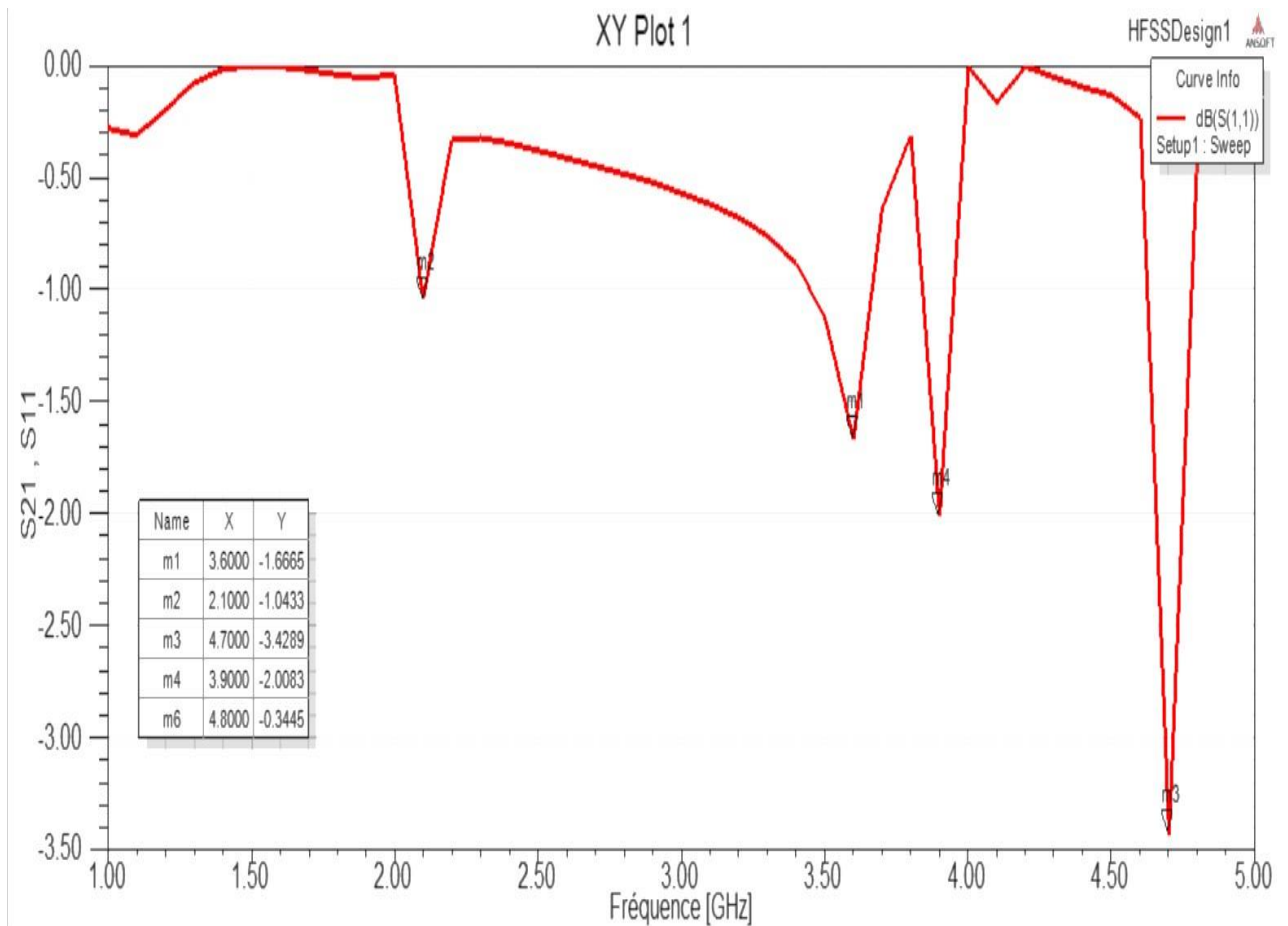


Figure 3.9 The Reflection coefficient (S11) of the proposed structure -Thickness = 0.035 mm

### 3.4.3 Simulation Result – Thickness = 0.05 mm

- **Resonance frequency:** Approximately 3.45 GHz
- **Reflection coefficient (|S11|):** Slightly deeper dip than the 0.035 mm case
- **Interpretation:** As thickness increases, the **effective permittivity** of the medium above the resonator increases, causing **stronger capacitive loading** and a **downward shift** in resonance frequency.

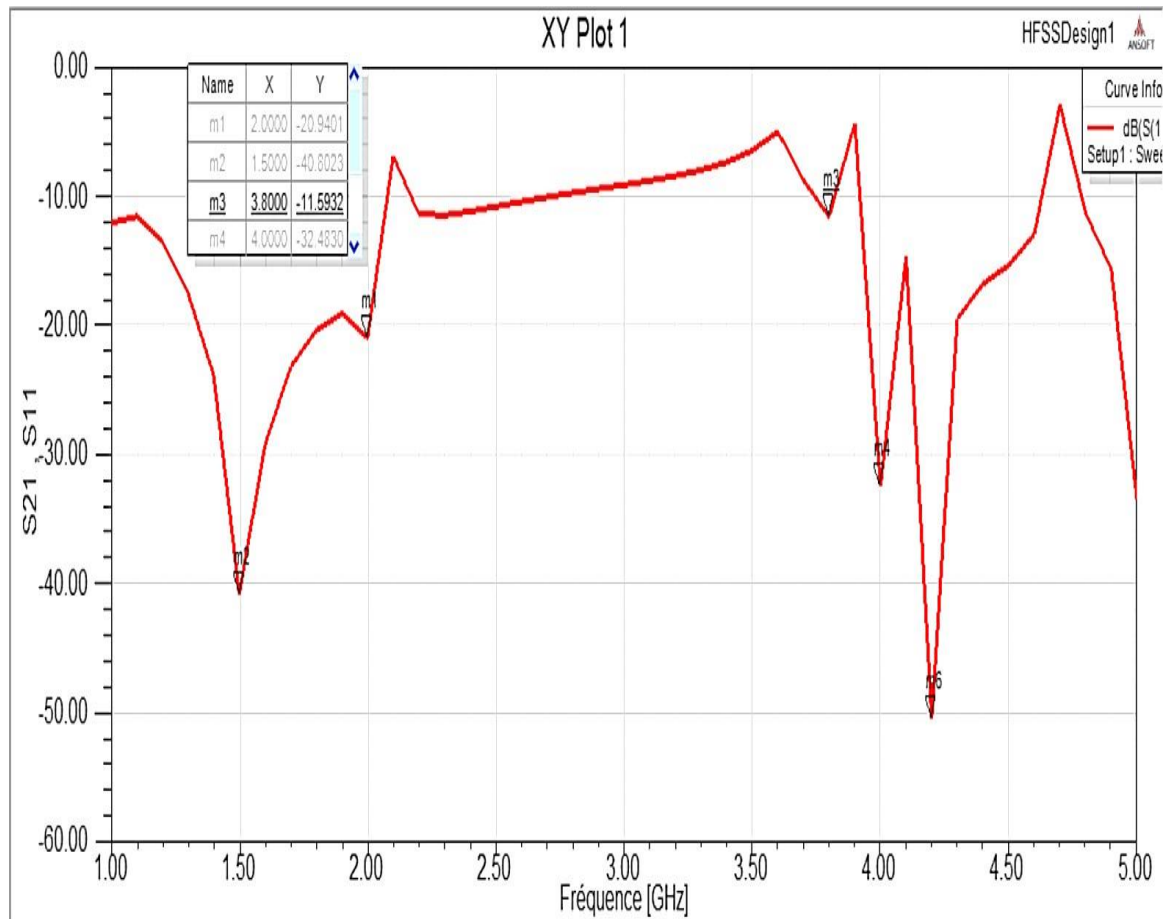


Figure 3.10 The Reflection coefficient (S11) of the proposed structure -Thickness = 0.05 mm

### 3.4.4 Simulation Result – Thickness = 0.1 mm

- **Resonance frequency:** Approximately 3.42 GHz
- **Reflection coefficient (|S11|):** Deepest dip, strongest resonance
- **Interpretation:** The thicker blood sample introduces **significant dielectric loading**, which further increases the sensor's effective capacitance. As a result, the resonance frequency

shifts **more notably toward the lower end** of the frequency band. This indicates the sensor's **high sensitivity** to variations in dielectric volume.

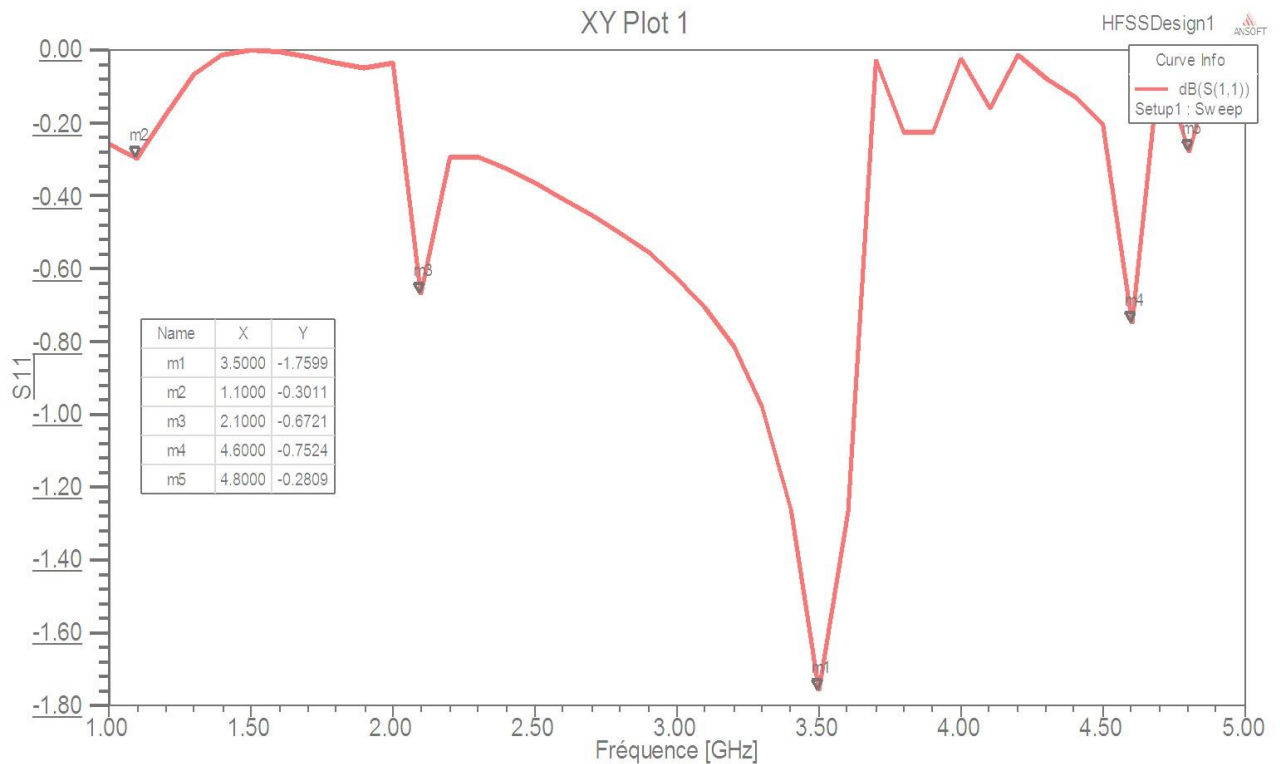


Figure 3.11 The Reflection coefficient (S<sub>11</sub>) of the proposed structure -**Thickness = 0.1 mm**

### ❖ Comparative Analysis

From these curves Figure 3.9 to Figure 3.11 , the following conclusions are evident:

- There is a **clear inverse relationship** between **blood concentration** and **resonance frequency**.
- Greater sample thickness enhances the **sensor's response**, as indicated by the **increased dip magnitude** and **resonance shift**.

- The shift appears to be **linear**, making the sensor suitable for **quantitative sensing applications** such as glucose monitoring.

### 3.5.Sensitivity Analysis

In this section, we evaluate the **sensitivity of the square metamaterial-based biosensor** in response to variations in two critical parameters:

- **Blood sample thickness** (volume)
- **Blood glucose concentration** (in mg/dL)

Sensitivity is a crucial performance metric that quantifies the **sensor's ability to detect small changes** in a given input parameter (e.g., glucose level or volume) by measuring shifts in either **resonance frequency ( $\Delta f$ )** or **reflection coefficient magnitude ( $\Delta|S_{11}|$ )**.

#### 3.5.1Sensitivity Based on Blood Sample Thickness

The **sensitivity in terms of thickness** is calculated using the following formula:

$$S_{th} = \frac{F_{sh} - F_{sL}}{U_h - U_l} \quad (3.6)$$

Where:

- $F_{sh}$ : Highest resonance frequency (corresponding to thinnest sample)
- $F_{sL}$  : Lowest resonance frequency (corresponding to thickest sample)
- $U_h$ : Minimum thickness (0.035 mm)
- $U_l$ : Maximum thickness (1.0 mm)

From simulation:

- Resonance at **0.035 mm = 3.436 GHz**
- Resonance at **1.0 mm = 3.372 GHz**

→ **Sensitivity with respect to thickness: 0.066 GHz per mm**

This indicates that for every 1 mm increase in blood sample thickness, the resonance frequency decreases by approximately **66 MHz**.

### 3.5.2 Sensitivity Based on Glucose Concentration (S<sub>glucose</sub>)

Unlike thickness, changes in **glucose concentration** do not produce a **significant frequency shift** but instead affect the **magnitude of |S<sub>11</sub>|** at the resonance frequency. Therefore, the sensor's glucose sensitivity is calculated using the difference in S<sub>11</sub> magnitude across the glucose range:

$$S_{\text{glucose}} = \frac{dB_{sh} - dB_{sl}}{G_h - G_l} \quad (3.7)$$

Where:

- dB<sub>sh</sub>: Magnitude of S<sub>11</sub> at **high glucose** (140 mg/dL)
- dB<sub>sl</sub>: Magnitude of S<sub>11</sub> at **low glucose** (80 mg/dL)
- G<sub>h</sub>–G<sub>l</sub>: Change in glucose level = 60 mg/dL

#### ❖ Interpretation of Results

- **Sensitivity increases with blood sample thickness.**
  - Thicker samples enhance **dielectric interaction**, amplifying the magnitude variation of the reflected signal.
- The biosensor shows **higher magnitude sensitivity** (|S<sub>11</sub>|) than **frequency shift** for glucose concentration changes.
- **Volume control** is crucial in achieving **reliable and repeatable measurements**. Standardization of droplet size or integration with a **microfluidic platform** could significantly improve real-world usability.

### **3.6 Conclusion**

The numerical methodology employed in this study involves the utilization of a proposed resonator that relies on a metamaterial (MTM) design for blood detection. By monitoring the variation in  $S_{11}$ , the proposed configuration has the potential to differentiate between different blood glucose concentrations. the proposed design indicates the predicted model is reliable. In future, the design can be improved by resizing and integrating it with the communication module for commercialization purposes.

## GENERAL CONCLUSION

This study validates the sensor's ability to detect of glucose concentrations and demonstrates its robustness, accuracy, and suitability for portable and continuous health monitoring applications.

The simulation results show the shift in resonant frequency correlated with glucose levels. Furthermore, the potential of this design is very important for diabetic monitoring technologies.

However, this research is not without its limitations. The proposed biosensor system, although promising in simulations, needs to be tested in real-world conditions to evaluate its practical effectiveness and response. Future research should focus on conducting real-life simulations and clinical trials to validate the biosensor's performance and refine its application.

As perspectives, this thesis underscores the significance of innovation and interdisciplinary collaboration in addressing critical healthcare challenges. By harnessing advanced technologies and research endeavors, such as integrating terahertz technology to surpass current millimeter wave capabilities and enhance biosensor precision, we are poised to advance biomedical engineering and significantly impact public health outcomes.

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## Résumé :

Ce mémoire présente la conception et la simulation d'un biocapteur innovant basé sur des métamatériaux, destiné à détecter la concentration de glucose dans le sang de manière non invasive. Le capteur utilise une structure en anneau fendu résonant à 3,5 GHz, sensible aux variations diélectriques induites par le glucose. Des simulations électromagnétiques utilisant le modèle de Debye ont permis de prédire les changements de fréquence de résonance selon les niveaux de glucose. Des tests expérimentaux avec des échantillons de sang humain ont validé les résultats simulés. Une analyse de sensibilité ainsi qu'une approche par réseaux de neurones artificiels ont été intégrées pour améliorer la précision des mesures. Ce travail confirme le potentiel du capteur pour des applications biomédicales portables et continues.

## Abstract :

This thesis explores the simulation and design of a metamaterial-based biosensor for non-invasive blood glucose detection. The sensor employs a split-ring resonator structure operating at 3.5 GHz, which exhibits high sensitivity to dielectric variations in biological samples. Electromagnetic simulations using the Debye model demonstrate a strong correlation between resonance frequency shifts and glucose concentration. Experimental validation using human blood samples supports the simulation findings. The study includes sensitivity analysis and artificial neural network integration for improved glucose level prediction. The proposed sensor proves accurate, robust, and well-suited for portable, continuous health monitoring applications.

## المخلص:

تتناول هذه المذكرة تصميم ومحاكاة مستشعر حيوي قائم على المواد الميتامادية للكشف عن تركيز الجلوكوز في الدم بطريقة غير جراحية. يعتمد المستشعر على ظاهرة الرنين الكهرومغناطيسي باستخدام حلقة رنينية مشقوقة، ويُظهر استجابة واضحة لتغيرات الخصائص العازلة للعينات البيولوجية. تم استخدام برامج محاكاة متقدمة ونموذج ديباي لتحليل التأثير الترددي للجلوكوز، وأظهرت النتائج توافقًا قويًا بين التردد الرنيني وتركيز الجلوكوز. شملت الدراسة أيضًا التحقق التجريبي باستخدام عينات دم بشرية وتحليل الحساسية وتطبيقات الشبكات العصبية الاصطناعية لتوقع التركيز. يثبت المشروع فعالية المستشعر ودقته وملاءمته للتطبيقات المحمولة والمراقبة الصحية المستمرة