

A Miniaturized Microwave Sensor Based on Concentric Semicircular Multi-Ring Resonator (CSMRR) for Dielectric Characterization of Liquid Samples

by

Md. Sajid Hasan (221016013)
Amena Akter (221016011)
Jannatun Nayeem Anjuman (221016008)
Jayed Ali (221016006)

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Under the supervision of
Rukhsana Choudhury

Lecturer

Department of Electrical and Electronic Engineering
University of Liberal Arts Bangladesh (ULAB)



DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
UNIVERSITY OF LIBERAL ARTS BANGLADESH (ULAB)

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DECLARATION

Project Title A Miniaturized Microwave Sensor Based on Concentric Semicircular Multi-Ring Resonator (CSMRR) for Dielectric Characterization of Liquid Samples
Authors Md. Sajid Hasan, Amena Akter, Jannatun Nayeem Anjuman and Jayed Ali
Student IDs 221016013, 221016011, 221016008 and 221016006
Supervisor Rukhsana Choudhury

We declare that this capstone project report entitled *A Miniaturized Microwave Sensor Based on Concentric Semicircular Multi-Ring Resonator (CSMRR) for Dielectric Characterization of Liquid Samples* is the result of our own work except as cited in the references. The capstone project report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Md. Sajid Hasan
221016013

Department of Electrical and
Electronic Engineering
University of Liberal Arts
Bangladesh (ULAB)

Amena Akter
221016011

Department of Electrical and
Electronic Engineering
University of Liberal Arts
Bangladesh (ULAB)

Jannatun Nayeem Anjuman
221016008

Department of Electrical and
Electronic Engineering
University of Liberal Arts
Bangladesh (ULAB)

Jayed Ali
221016006

Department of Electrical and
Electronic Engineering
University of Liberal Arts
Bangladesh (ULAB)

Date: December 28, 2025

CERTIFICATE

This is to certify that the capstone project report entitled **A Miniaturized Microwave Sensor Based on Concentric Semicircular Multi-Ring Resonator (CSMRR) for Dielectric Characterization of Liquid Samples**, submitted by **Md. Sajid Hasan** (Student ID: 221016013), **Amena Akter** (Student ID: 221016011), **Jannatun Nayeem Anjuman** (Student ID: 221016008), and **Jayed Ali** (Student ID: 221016006) are undergraduate students of the **Department of Electrical and Electronic Engineering** has been examined. Upon recommendation from the examination committee, we hereby grant our approval of it as the presented work and the submitted report meet the requirements for its acceptance in full fulfillment for the degree of *Bachelor of Science (B.Sc.) in Electrical and Electronic Engineering*.

Rukhsana Choudhury
Lecturer
Department of Electrical and Electronic
Engineering
University of Liberal Arts Bangladesh (ULAB)



External Supervisor
Md. Nizam Uddin Tanim
Lecturer
Department of Electrical and Electronic Engineering
University of Dhaka

Dr. Muhammad Golam Kibria, SMIEEE
Professor & Head (Acting), Electrical and
Electronic Engineering
Department of Electrical and Electronic Engineering
University of Liberal Arts Bangladesh (ULAB)

Place: Dhaka
Date: December 28, 2025

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Md. Sajid Hasan and Amena Akter

University of Liberal Arts Bangladesh (ULAB)

Date: December 28, 2025

Dedicated to me
for believing in myself.

– Md. Sajid Hasan

Dedicated to
my beloved parents

– Amena Akter

To my mother
*who chose to be strong for her
daughters.*

– Jannatun Nayeem Anjuman

To my dearest mother,
*with deepest gratitude for her
unconditional love.*

– Jayed Ali

ABSTRACT

Reliable dielectric characterization of small-volume liquid samples is crucial for chemical, biomedical, and environmental sensing applications, especially when a real-time, quick, simple, and cost-effective fabrication method is required. In this study, a compact microwave liquid sensor based on a Concentric Semi-Circular Multi-Ring Resonator (CSMRR) is developed for accurate dielectric measurement of liquid samples. The sensor is built on an RT/duroid 5880 substrate and operates at a notch resonance of 3.8 GHz under unloaded conditions. The multilayer ring structure enhances electric-field confinement within the inter-ring gaps, increasing the interaction between the resonator and the liquid under test. Experimental measurements confirm a maximum frequency shift of 1.68 GHz when transitioning from unloaded condition to DI water, which demonstrates strong dielectric coupling. The sensor performance is evaluated using ethanol–water binary mixtures with ethanol concentrations ranging from 10% to 90%, where systematic variations in both notch frequency and transmission coefficient magnitude ($|S_{21}|$) are observed. A linear and quadratic mathematical calibration model is developed to extract the complex permittivity of liquid samples from measured resonance shifts and attenuation-depth variations. The quadratic model achieves improved accuracy, yielding an average percentage error of 2.11% for the real part and 0.80% for the imaginary part of permittivity. The proposed sensor attains an average sensitivity of 0.892% while a relative permittivity range of 5-80, requiring only 40 μL of liquid sample. The compact sensor footprint of 26 mm $\times$ 28 mm, low fabrication cost, and strong agreement with literature values highlight strong potential for real-time, label-free, simple, and cost-effective liquid dielectric characterization in biomedical diagnostics, chemical analysis, and quality-control monitoring.

Keywords: Microwave Sensor, Concentric Semi-Circular Multi-Ring Resonator (CSMRR), Liquid Dielectric Characterization, Metamaterial Resonator, Ethanol–Water Mixtures, Complex Permittivity Extraction, Resonance Frequency Shift, Sub-6 GHz Sensing, Calibration Model, Low-Volume Liquid Sensing

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Chapter 1

Introduction

1.1 Background

Dielectric characterization of liquid materials is an essential technique in many scientific and industrial domains, as the dielectric properties of a material are closely related to its molecular structure, composition, and physical state. Parameters such as complex permittivity provide valuable information for applications including chemical analysis, food quality monitoring, biomedical diagnostics, pharmaceutical processing, and environmental sensing [1–3]. Accurate measurement of these properties enables non-destructive and real-time evaluation of liquid samples, which is highly desirable in modern sensing systems.

Conventional dielectric measurement techniques include transmission line methods, resonant cavity techniques, open-ended coaxial probes, and free-space measurement systems [4]. Although these methods are well established, they typically require expensive instrumentation, precise calibration standards, and controlled laboratory environments. In addition, some methods demand large sample volumes or involve complex measurement procedures, making them unsuitable for portable or low-cost applications [5].

Microwave sensors have emerged as a pivotal technological solution for the characterization of material properties, finding widespread application in areas such as healthcare diagnostics, chemical analysis, and industrial process monitoring [6]. These sensors operate by exploiting the interaction between electromagnetic fields and materials, typically within a frequency range extending from 0.3 to 300 gigahertz (GHz) spectrum [7]. Microwave sensing techniques are highly valued due to their non-invasive nature, cost effectiveness, compact form factor, high

measurement accuracy, and relative simplicity in fabrication and experimental implementation [8]. Based on their operational principles, microwave sensors are broadly classified into broadband sensors and resonance-based sensors. Among these, resonance-based sensors operate over a narrow frequency band and leverage strong electromagnetic field confinement around the sensing region, resulting in high sensitivity to changes in dielectric loading [9]. Consequently, even minor variations in the dielectric properties of the material under test lead to measurable shifts in resonant or notch frequency and transmission or reflection characteristics. Furthermore, recent research trends highlight the development of multivariable-response microwave sensors that aim to overcome the limitations of conventional sensor arrays by reducing hardware complexity. These multi-variable sensors offer compact, low-cost alternatives with improved stability, reduced drift, and enhanced integration capability [10].

In recent years, metamaterial-inspired resonators such as Complementary splitting resonators (CSRRs) have been widely explored for sensing applications [11]. CSR Rs offer strong electric-field confinement, a compact footprint, and enhanced sensitivity to nearby materials. Their planar structure allows easy fabrication using standard printed circuit board (PCB) technology, significantly reducing manufacturing costs. Furthermore, CSRR-based sensors have demonstrated promising performance in detecting small changes in the dielectric properties of liquids, making them suitable for compact and low-cost sensing platforms [12].

1.2 Problem statement

Accurate dielectric characterization of liquid samples is essential for applications in chemical analysis, food quality assessment, biomedical diagnostics, and industrial process monitoring. However, existing dielectric measurement techniques continue to face practical limitations that restrict their widespread adoption. Conventional laboratory-based methods, such as transmission line, resonant cavity, and open-ended coaxial probe techniques, rely on expensive instrumentation, bulky setups, and skilled operation, making them unsuitable for low-cost, portable, and field-deployable applications [4,5].

Widely used open-ended coaxial probe techniques suffer from reduced accuracy when measuring low-loss liquids and small sample volumes. Their performance is

also highly sensitive to surface contact conditions and air gaps, which introduce measurement uncertainty [13]. Resonant cavity methods offer high precision but are constrained by narrow operational bandwidths and rigid sample holder requirements, limiting their flexibility and applicability to practical liquid sensing scenarios .

Recent advances in microwave and metamaterial-inspired sensors have demonstrated improved sensitivity to dielectric variations. The global microwave sensor market represents a substantial and growing industry, with its valuation estimated at USD 7.2 billion in 2024 and projected to increase to USD 13.2 billion by 2033, reflecting a strong Compound Annual Growth Rate (CAGR) of 6.8% between 2025 and 2033 [14]. This expansion corresponds with trends observed in the broader microwave device sector, which is projected to increase from USD 8.42 billion in 2024 to USD 14.89 billion by 2034, exhibiting a CAGR of 5.87%; microwave sensor typically function within the frequency spectrum of 300 MHz to 300 GHz [15]. Central to motion detection technology, as exemplified by the 10.525 GHz HB100X module, is the Doppler radar principle, which utilizes frequency shifts in reflected microwave signals. This principle provides critical benefits such as temperature insensitivity, operational reliability in adverse conditions like fog and dust, and extended detection ranges [16]. On a global scale, the market encompasses active microwave sensor that actively emit signals for precise measurements and are favored for mission-critical applications, as well as passive sensors that detect naturally emitted signals, enabling non-invasive and energy-efficient monitoring, notably in meteorological satellite systems [14]. Diverse technological methodologies are employed, including Microwave Doppler, Frequency Modulated Continuous Wave (FMCW), Phase Shift, and Ultra-Wideband sensor technologies, which are particularly pertinent to microwave flow sensors utilized across multiple sectors such as oil and gas, water and wastewater management, and the food and beverage industry [16]. Moisture measurement is identified as a key application domain of paramount importance [17]. Growth is driven by increasing adoption in automotive safety systems (ADAS, autonomous vehicles), industrial automation (process control, material handling), and expanding applications in security and surveillance and healthcare, with Asia Pacific leading regionally by accounting for approximately 34% of revenue in 2024, followed by North America and Europe [14]. Furthermore, the rapid rollout of 5G telecommunications infrastructure substantially amplifies market demand. In the

context of Bangladesh, various commercially available microwave sensor modules are accessible, including the 10.525 GHz HB100X microwave sensor Module retailing at BDT 1,190 and the HB100 MS 10.525 GHz Doppler Radar Motion Detector priced at BDT 620; the HB100X model offers a detection range of 5 to 10 meters, whereas the HB100 extends this range to 20 meters. Additionally, radar-based human presence or motion sensor modules operating at 24 GHz are available at price points ranging from BDT 730 to BDT 2,950 [16].

Therefore, the core problem addressed in this project is the lack of an affordable and reliable microwave sensing platform that leverages CSRR structures to accurately characterize the dielectric properties of liquid samples using a compact and scalable design suitable for practical applications.

1.3 Objective

The primary objective of this research is to design, optimize, fabricate, and validate a low-cost microwave sensor based on a Concentric Semicircular Multi-Ring Resonator (CSMRR) for accurate dielectric characterization of liquid samples. The proposed sensor is designed to operate within a specified frequency range. It is optimized in CST Microwave Studio to achieve strong electric-field confinement, efficient field-sample interaction, and adequate penetration depth. An equivalent lumped-element circuit model is developed and fine-tuned in Advanced Design System (ADS) to represent the sensor's electromagnetic behavior accurately. The research further aims to fabricate a compact sensor prototype using standard printed circuit board technology and experimentally validate its simulated S-parameters. Performance evaluation includes establishing a calibration model using reference liquid samples that cover a relevant permittivity range, assessing key metrics such as average sensitivity, average error, and standard deviation through systematic experimentation and mathematical modeling. Finally, the study demonstrates the capability of the proposed sensor to detect subtle dielectric variations in representative liquid samples, such as transformer oil, by correlating resonant frequency shifts with permittivity changes and reflection coefficient variations with conductivity, thereby highlighting its potential as a compact and cost-effective solution for real-time liquid dielectric characterization.

1.4 Project Outlines

Chapter 1 introduces the background and motivation for the research, emphasizing the importance of dielectric characterization of liquid materials using microwave sensing techniques. This chapter outlines the limitations of conventional dielectric measurement methods, defines the problem statement, and clearly states the objectives and scope of the proposed CSMRR-based microwave sensor.

Chapter 2 presents a detailed literature review on existing dielectric measurement techniques and microwave-based liquid sensing approaches. It discusses conventional methods as well as recent advancements in metamaterial-inspired resonators, particularly split-ring resonators and CSRR-based sensors. A comparative analysis of related works is included to highlight existing research gaps and justify the proposed sensor design.

Chapter 3 describes the methodology and theoretical framework of the proposed research. This chapter explains the operating principle of the Concentric Semi-Circular Multi-Ring Resonator (CSMRR), the sensor design process, electromagnetic simulations, equivalent circuit modeling, and optimization procedures. The design parameters and simulation results are presented to validate the sensor configuration before fabrication.

Chapter 4 focuses on the fabrication, experimental setup, and performance evaluation of the proposed sensor. It details the PCB fabrication process, measurement procedures using a portable VNA, and the response of the sensor under different liquid samples. Numerical modeling, calibration techniques, sensitivity analysis, error evaluation, and comparison with existing sensors are also discussed in this chapter.

Chapter 5 concludes the project by summarizing the key findings and contributions of the research. It discusses potential future research directions, including sensor optimization, integration with compact measurement systems, and extension to other liquid materials and real-time sensing applications.

Chapter 2

Literature Review

2.1 Overview

Dielectric characterization of liquid samples is a fundamental process in numerous scientific and engineering disciplines, including materials science, biomedical engineering, power systems, and chemical analysis. The dielectric response of a material reflects its interaction with an applied electric field and provides valuable insight into molecular composition, polarization mechanisms, and loss behavior. As reported by [18], permittivity is a key parameter that describes how a material responds to an external electric field, making dielectric characterization essential for understanding intrinsic material properties. The complex permittivity consists of a real part, which represents the ability of a material to store electrical energy, and an imaginary part, which accounts for dielectric losses arising from conduction and relaxation phenomena. Accurate determination of these parameters is critical for detecting contaminants, monitoring degradation in expensive insulating liquids, ensuring purity in chemical processes, and analyzing biological samples with high precision.

2.2 Conventional Dielectric Measurement Techniques

Historically, several conventional techniques have been employed for the dielectric characterization of liquids, including resonant-cavity methods, open-ended coaxial probe techniques, and transmission-line-based approaches. Although these methods are well established and widely used, each presents inherent limitations

in terms of cost, system complexity, and sample handling. Cavity resonator techniques are known for their high measurement accuracy and sensitivity. However, as highlighted by [19], such systems are expensive, bulky, and require precisely machined resonant structures and controlled experimental environments, making them unsuitable for portable or lab-on-a-chip applications. Additionally, [20] reported that resonant cavity methods can suffer from the excitation of higher-order modes when characterizing high-permittivity materials, while high-loss liquids significantly degrade the quality factor (Q-factor), thereby reducing the accuracy of the measurement. The open-ended coaxial probe technique is another commonly used approach due to its broadband operation and relative ease of implementation. [21] noted that this method typically requires the probe to be immersed in the liquid under test (LUT), necessitating a minimum sample volume that may not be feasible for biological or chemically sensitive applications. Furthermore, the accuracy of coaxial probe measurements is highly dependent on the proper contact between the probe and the sample, and air gaps or surface irregularities can introduce significant uncertainties. Transmission line methods have also been utilized for dielectric measurements; however, [22] emphasized that these approaches often involve complex calibration procedures and may be partially destructive to the test material. [20] further reported challenges associated with sealing liquid samples within transmission line fixtures, as well as the need for precisely fabricated sample holders to prevent leakage and ensure measurement repeatability. Together, these limitations have motivated the search for alternative techniques that are compact, low-cost, and suitable for small-volume liquid characterization.

2.3 Advancements in Metamaterial Based Microwave Sensors

To overcome the drawbacks of conventional dielectric measurement techniques, recent research has increasingly focused on planar microwave sensors, particularly those based on metamaterial-inspired resonant structures such as Split-Ring Resonators (SRRs) and CSRRs. These resonators offer strong electromagnetic field confinement, compact size, and high sensitivity to dielectric loading, making them attractive for liquid sensing applications.

[19] proposed a low-cost Multiple Complementary Split-Ring Resonator (MC-SRR) sensor operating at 2.45 GHz, where a glass capillary tube was strategically positioned within the region of maximum electric field intensity. This approach eliminated the need for complex microfluidic channel fabrication while maintaining good sensitivity. Similarly, [23] developed a sensor based on a triple-ring CSRR configuration designed to operate in the Industrial, Scientific, and Medical (ISM) bands at 1.2 GHz and 2.4 GHz. Their results demonstrated that increasing the number of resonator rings enhances electric field density and improves the Q-factor, leading to improved sensing performance.

[18], introduced an innovative CSRR design incorporating curved slots to intensify electric field confinement further. This structural modification significantly enhanced sensitivity for both solid and liquid samples, highlighting the importance of resonator geometry optimization in microwave sensor design.

Significant efforts have been directed toward minimizing required sample volume while simultaneously improving sensor sensitivity. [24] developed a sensor incorporating an interdigital capacitor (IDC) integrated within a microfluidic channel, enabling dielectric characterization of nanoliter-scale liquid volumes up to 25 GHz. This design was particularly suited for biological cell analysis, though it required relatively complex microfluidic integration.

[25] utilized a triple-ring CSRR with a curved microstrip feed line to enhance electromagnetic excitation, achieving high sensitivity for characterizing ethanol and methanol concentrations. [22] proposed a double SRR configuration in which the microstrip feed line overlapped one side of the outer ring, enabling sub-wavelength resonance at 1.9 GHz and significantly improving measurement sensitivity. [20] further demonstrated a multi-element CSRR sensor employing three circular split rings and a quartz glass tube, allowing characterization of high-permittivity and high-loss liquids by partially filling the resonator.

Beyond resonator design, researchers have explored alternative interrogation and detection mechanisms to simplify measurement systems and reduce reliance on expensive equipment such as VNAs. [26], proposed a differential microwave sensor system in which a demodulator converts the RF signal power into a DC voltage, thereby eliminating the need for wideband frequency sweeps and reducing sensitivity to environmental variations. [27] introduced a single-frequency amplitude-modulation sensor based on a CSRR-loaded stepped impedance resonator (SIR),

where voltage amplitude served as the sensing variable. This approach provided a cost-effective alternative to conventional frequency-domain measurements.

[21] presented a droplet-based sensing technique using a semi-lumped meander open CSRR (MOCSRR) operating at sub-gigahertz frequencies. This method required only a small liquid droplet for characterization, avoiding the fabrication complexity associated with microfluidic channels while maintaining acceptable sensitivity.

2.4 Comparative Analysis of Existing Approaches

A comparative analysis of the reported works reveals diverse strategies for enhancing sensitivity, simplifying sample handling, and reducing system complexity. In terms of sensitivity enhancement, [18] achieved a sensitivity of approximately 0.78% for liquid samples through curved-slot field confinement, whereas [25] reported a higher sensitivity of $7.321 \text{ MHz}/\epsilon_r$ using a triple-ring CSRR with a curved feed structure. [27] demonstrated an amplitude-based sensitivity of $4 \text{ mV}/\%$ for isopropanol detection, validating the feasibility of single-frequency sensing techniques.

Regarding fabrication and sample handling, [19] and [23], emphasized cost-effective implementations using FR-4 substrates and capillary tubes, whereas [24], prioritized extreme miniaturization at the expense of increased fabrication complexity. Static liquid handling approaches, such as droplet placement and glued sample holders, simplify operation but may limit throughput, while flow-based microfluidic systems offer advantages for continuous monitoring applications despite higher fabrication demands.

Overall, while existing microwave and metamaterial-based sensors demonstrate promising performance, challenges remain in achieving an optimal balance between sensitivity, fabrication simplicity, sample handling flexibility, and system cost. These challenges highlight the need for further research into low-cost, compact, and robust microwave sensors capable of reliable dielectric characterization of liquid samples.

For ease of understanding, the main characteristics of selected existing works are summarized and shown in Table 2.1.

Table 2.1: Overview of CSRR and SRR-based Microwave Liquid Sensing Sensors

Reference (Year)	Sensor Topology	Frequency	Sample Handling	Key Features and Detection Principle
[18],(2024)	CSRR with curved slots	2.45 GHz	PDMS microfluidic channel	Curved slots confine electric field; improved sensitivity for solids and liquids
[19],(2020)	Multiple CSRR (MC-SRR)	2.45 GHz	Glass capillary tube	Low-cost FR-4 substrate; frequency-shift sensing; avoids complex microfluidics
[20],(2022)	Multi-element CSRR (three rings)	2.96 GHz	Fused quartz glass tube	Partial filling supports high-loss liquids; improved measurement feasibility
[21],(2019)	Semi-lumped meander OCSRR	350 MHz	Dropping-based (static)	Droplet method avoids channels; low-frequency operation; small sample volume
[22],(2018)	Double split-ring resonator	1.9 GHz	Plastic pipe	Transmission-based sensing using magnitude and phase; compact sub-wavelength design
[23],(2021)	Triple-ring CSRR	1.2 and 2.4 GHz	ABS sample holder	Optimized for ISM bands; simple structure for estimating complex permittivity
[24],(2022)	Interdigitated capacitor (IDC)	0.2–25 GHz	SU-8 microfluidic channel	Reflection-based sensing; nanoliter liquid analysis; suitable for biological samples
[25],(2023)	Triple-ring CSRR	2.5 GHz	Polypropylene tube	Curved feed improves excitation; high sensitivity for liquid permittivity characterization
[26],(2024)	Differential modified SRR	1.79 GHz	Flow-based	Demodulator-based DC output; removes need for VNA; reduces environmental noise
[27],(2021)	CSRR-loaded stepped impedance resonator	1.125 GHz	Microfluidic channel	Single-frequency amplitude sensing; envelope detector converts RF to voltage

Chapter 3

Methodology

3.1 Project Design

The Concentric Semi-Circular Multi-Ring Resonator (CSMRR) is developed using a step-by-step design and validation workflow. The process includes electromagnetic simulation, equivalent circuit modeling, and experimental verification. This sequence ensures that the sensor operates at the desired resonance while maintaining a compact planar structure. The resonator is formed by five concentric semicircular rings with narrow split gaps. These gaps act as capacitive regions, concentrating the electric field near the resonator surface. When a liquid sample is placed over this region, the effective permittivity seen by the resonator changes. This change alters the resonant frequency and quality factor of the sensor. The measured shifts are used to characterize the dielectric properties of the liquid sample. Based on the defined project scope, the following tasks were carried out in this work:

1. A compact multi-ring microwave sensor with physical dimensions of 26 mm $\times$ 28 mm was designed to operate at a notch resonance of 3.8 GHz.
2. The sensing mechanism is based on the redistribution of the resonator's electromagnetic field when a liquid sample is introduced in the high-field region of the sensor.
3. A mathematical model was developed to relate the resonant frequency shift and the variation in transmission magnitude (attenuation depth) to changes in the complex permittivity of the liquid sample.

4. The operating (unloaded) frequency of 3.8 GHz lies within the sub-6 GHz band, which is widely used in emerging 5G communication systems and supports future compatibility with microwave-based IoT sensing platforms.

3.1.1 Overall Project Plan

The project was carried out in five sequential phases. These phases cover design, simulation, fabrication, measurement, and dielectric characterization.

1. **Initial Design and Benchmarking:** The semicircular resonator geometry was designed in CST Microwave Studio. The structure was optimized to achieve a notch resonance at 3.8 GHz under no-load conditions.
2. **Circuit Validation:** The simulated resonator was represented using a lumped-element equivalent circuit in Advanced Design System (ADS). This model was used to analyze the resonance behavior of the sensor.
3. **Fabrication:** The optimized design was fabricated on an RT/duroid 5880 substrate using standard printed circuit board fabrication techniques.
4. **Experimental Analysis:** The fabricated sensor was characterized using a Vector Network Analyzer (VNA). The measured S-parameters were used to verify the notch resonance near 3.8 GHz.
5. **Characterization and Modeling:** The sensor was tested with liquid samples including normal water, deionized water, ethanol, and their binary mixtures. The measured response was used to develop a mathematical model for dielectric permittivity extraction.

3.1.2 Design Flowchart

The overall workflow of the research is shown in the flowchart below. It presents the sequence of design, simulation, fabrication, measurement, and data analysis steps followed in this work.

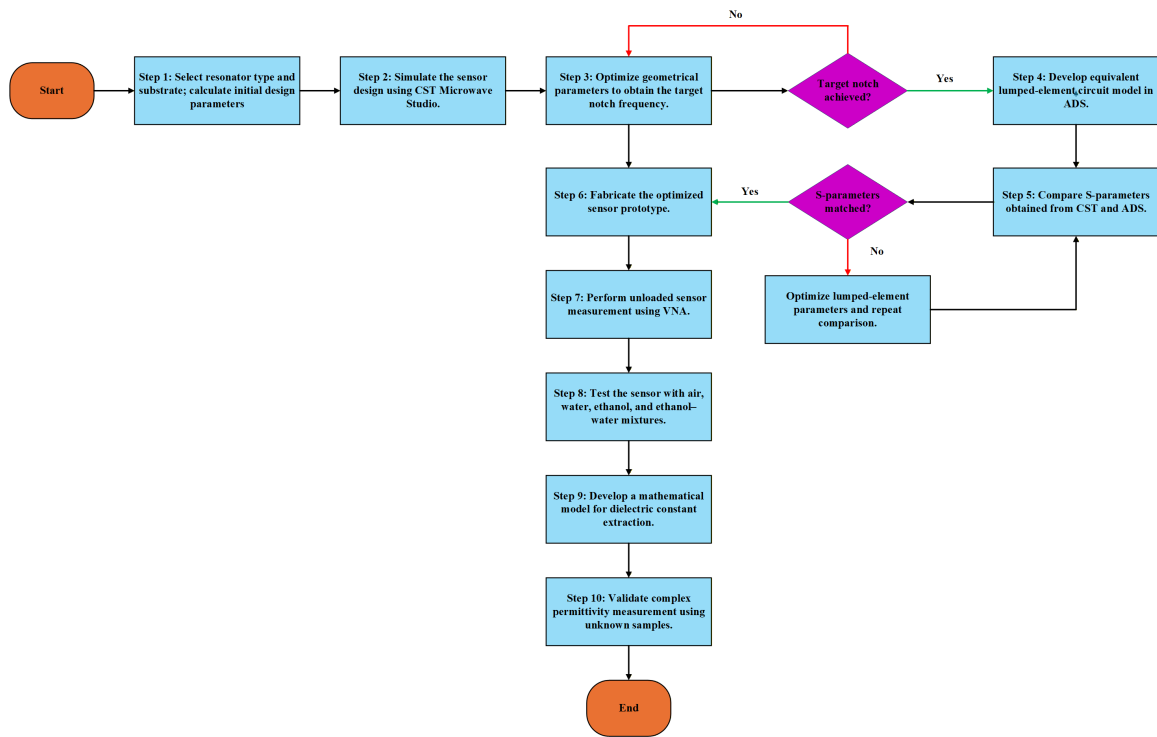


Figure 3.1: Flowchart for the proposed methodology

3.2 Basic Principle and Sensor Design

3.2.1 Basic Principle

The resonant structure of a sensor operates based on the principle of equal distribution of electric and magnetic field energies, as described by electric circuit theory. Resonance occurs when these energies are balanced. However, when a liquid is in the vicinity of the sensor, it disturbs the electromagnetic field distribution, resulting in shifts in the operating frequency and the quality factor (Q) from their unloaded values.

This interaction is mathematically expressed as follows [28]:

$$\frac{\Delta f_{ns}}{f_{nw}} + j \left(\frac{1}{2Q_{nw}} - \frac{1}{2Q_{ns}} \right) = \frac{\int_v (-\Delta\epsilon_{ns} E_w E_s + \Delta\mu_{ns} H_w H_s) dv}{\int_v (\epsilon_w |E_w|^2 - \mu_w |H_w|^2) dv} \quad (3.1)$$

Where:

- f_{nw} represents the notch frequency when the sensor is unloaded (air),
- f_{ns} is the frequency with solution samples (normal water, DI water, ethanol, DI water and ethanol binary mixture),
- E_w, H_w are the electric and magnetic fields in unloaded sensor (air),
- E_s, H_s are the fields when the solution sample perturbs the sensor in an aqueous solution of volume v .

It is crucial to maximize the resonant intensity of the structure for optimal performance of the planar resonator sensor. The test sample must also be precisely positioned within the resonant electromagnetic field. This ensures the strongest possible interaction between the sample and the sensor, resulting in a more significant shift in notch frequency and enabling accurate detection of material properties. The areas of the resonator where strong electric and magnetic fields are observed are susceptible to dielectric variations in the sample. This results in a detectable frequency shift, which forms the core principle of resonant sensor-based detection systems [29].

Table 3.1: Technical Specifications of the RT/duroid 5880 Substrate

Parameter	Relative Permittivity	Dielectric Loss Tangent	Substrate Height	Copper Cladding
Symbol	ϵ_r	$\tan \delta$	h	t
Value	2.20 ± 0.02	0.0009	1.575 mm	0.0175 mm

3.2.2 Design of the sensor

The dielectric substrate was selected based on its impact on resonator loss and sensing performance. Substrate permittivity and loss tangent directly affect the quality factor and field distribution of a microwave sensor. Although FR4 is commonly used in low-cost designs, it introduces higher dielectric loss at microwave frequencies.

In this work, Rogers RT/droid 5880 was used as the substrate material. It is a glass microfiber reinforced PTFE composite with a relative permittivity of 2.20 and a dissipation factor of 0.0009. The low permittivity promotes stronger fringing electric fields above the resonator surface. As reported by [30], increased fringing fields enhance interaction with materials placed on the sensor surface. Since the liquid under test is positioned directly over the resonator, this property improves dielectric sensitivity.

The electrical and physical parameters of the selected substrate are listed in Table 3.1. These parameters were used in all electromagnetic simulations and fabrication processes to ensure consistency between simulated and measured results.

Based on the selected substrate properties, the resonator geometry was tuned to achieve the desired operating frequency. The proposed sensor is designed to operate at a fundamental notch frequency of 3.8 GHz under unloaded conditions. This frequency was selected to ensure a measurable response when the sensor is exposed to high-permittivity liquid samples. When aqueous liquids are introduced, the resonant frequency shifts by up to 1.68 GHz due to the strong interaction between the fringing electric field and the sample. Selecting an initial resonance at 3.8 GHz ensures that the shifted response remains within a practical microwave frequency range for accurate measurement. The operating frequency lies within the sub-6 GHz spectrum and overlaps with the n77 and n78 frequency bands used in 5G communication systems. This frequency selection supports future compatibility with microwave sensing platforms operating in 5G-enabled environments.

Based on the selected operating frequency, the resonator geometry was finalized through electromagnetic optimization. The physical layout of the CSMRR sensor was finalized using CST Microwave Studio. The optimized design was prepared for fabrication based on the simulated resonance characteristics. The overall substrate dimensions were fixed at 26 mm $\times$ 28 mm. The front and back views of the fabricated sensor layout are shown in Figure 3.2.

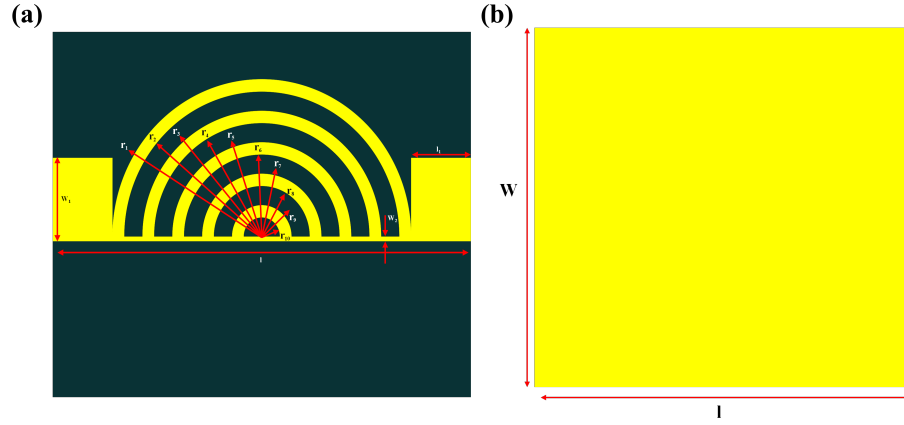


Figure 3.2: Schematic of the proposed CSMRR sensor: (a) Back view, and (b) Front view.

The optimized geometric parameters corresponding to the layout shown in Figure 3.2 are listed in Table 3.2.

Table 3.2: Optimized geometric parameters of the sensor

Parameter	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8
Value (mm)	10	9.2	8	7.2	6	5.2	4	3.2
Parameter	r_9	r_{10}	W	W_1	W_2	l	l_1	
Value (mm)	2	1.2	28	5	0.3	26	4	

This multi-ring architecture enables the sensor to operate with a minute volume of liquid because the field is trapped in the four narrow gaps between the five rings. Even a single droplet on this array alters the system's total capacitance. This change causes the apparent frequency shifts observed at 3.8 GHz. To examine the electromagnetic behavior of the optimized geometry, the electric field distribution was analyzed at the resonance frequency. This analysis is vital for identifying the regions of maximum sensitivity. The electric-field distribution of the CSMRR sensor

at resonance is shown in Figure 3.3. The field magnitude is concentrated along the outer semicircular rings, particularly near the split-gap region. This high-field region determines the optimal location for the liquid sample holder.

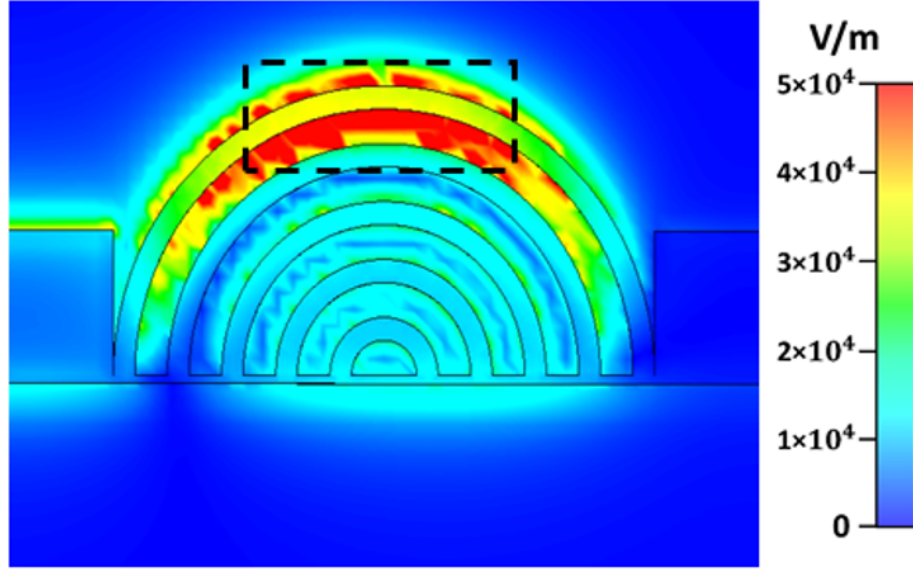


Figure 3.3: Simulated electric field of the CSMRR sensor at 3.8 GHz.

The liquid sample holder was positioned above the region of maximum electric field intensity, as indicated in Figure 3.3. Placing the sample in this location maximizes interaction between the fringing electric field and the liquid under test. Variations in the liquid's dielectric properties therefore produce a more substantial perturbation in the sensor's resonant response.

3.2.3 Equivalent circuit model and verification

Following the microstrip resonator modeling techniques proposed by [31], the physical structure is represented as a shunt-connected resonant network. The multi-ring CSMRR is modelled as a parallel combination of inductive and capacitive branches, as shown in Figure 3.4.

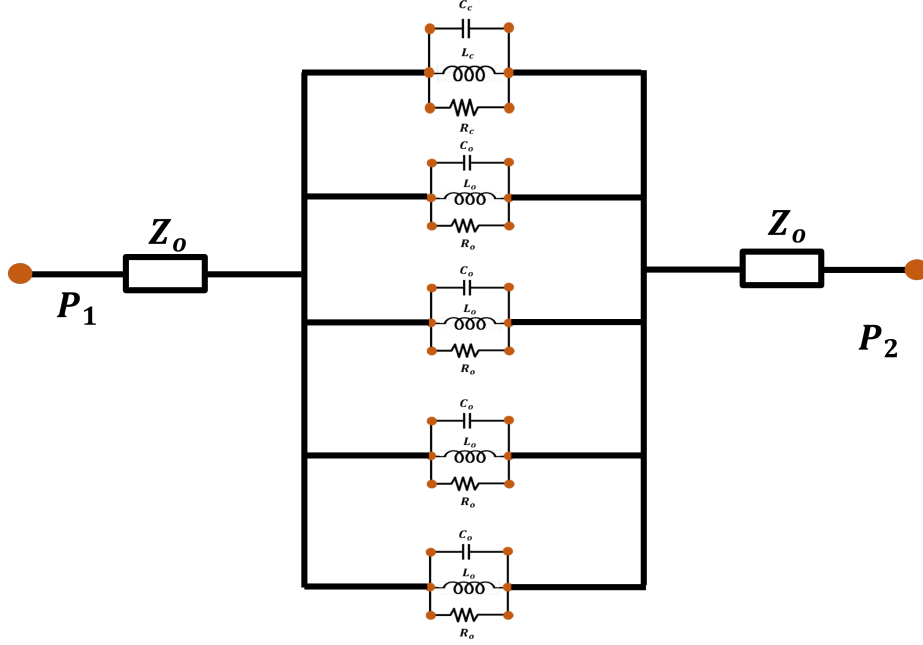


Figure 3.4: Equivalent circuit of the proposed CSMRR sensor.

According to the derivation presented in the reference study, the lumped element values of the resonator are determined by the characteristic impedance (Z_0) and the angular resonant frequency (ω_0). The notations for the five-ring architecture are defined as follows:

- **Open Ring Branch (L_0, C_0, R_0):** Represents the outermost split-ring.
- **Closed Ring Branch (L_e, C_e, R_e):** Represents the internal concentric rings.

Based on [31], the equations used to calculate the lumped inductance (L) and capacitance (C) are:

$$C_c = \frac{\pi}{Z_0 \omega_0} \quad (3.1)$$

$$C_o = \frac{\pi}{2Z_0 \omega_0} \quad (3.2)$$

$$L_c = \frac{1}{\omega_0^2 C_e} \quad (3.3)$$

$$L_o = \frac{1}{\omega_0^2 C_0} \quad (3.4)$$

Where Z_0 is the characteristic impedance of the 50Ω feedline and $\omega_0 = 2\pi f_0$ with $f_0 = 3.8$ GHz. Substituting these values into the equations yields:

Capacitances:

$$C_c = \frac{\pi}{Z_0 \omega_0} = \frac{3.1416}{50 \times 2 \times 3.1416 \times 3.8 \times 10^9} \approx 2.63 \text{ pF}$$

$$C_o = \frac{\pi}{2Z_0 \omega_0} = \frac{3.1416}{2 \times 50 \times 2 \times 3.1416 \times 3.8 \times 10^9} \approx 1.13 \text{ pF}$$

Inductances:

$$L_C = \frac{1}{\omega_0^2 C_c} = \frac{1}{(2 \times 3.1416 \times 3.8 \times 10^9)^2 \times 2.63 \times 10^{-12}} \approx 0.66 \text{ nH}$$

$$L_o = \frac{1}{\omega_0^2 C_o} = \frac{1}{(2 \times 3.1416 \times 3.8 \times 10^9)^2 \times 1.31 \times 10^{-12}} \approx 1.33 \text{ nH}$$

The resistor values (R_0 , R_e) account for the dielectric and conductor losses associated with the RT/duroid 5880 substrate. These lumped elements effectively translate the physical 3.8 GHz resonator into an equivalent discrete electrical network suitable for circuit-level analysis and verification.

With the lumped-element values determined, the resonator was modelled in ADS to create the equivalent circuit. To evaluate the accuracy of this representation, the S-parameter response of the equivalent circuit was compared with the full-wave simulation results obtained from CST Microwave Studio.

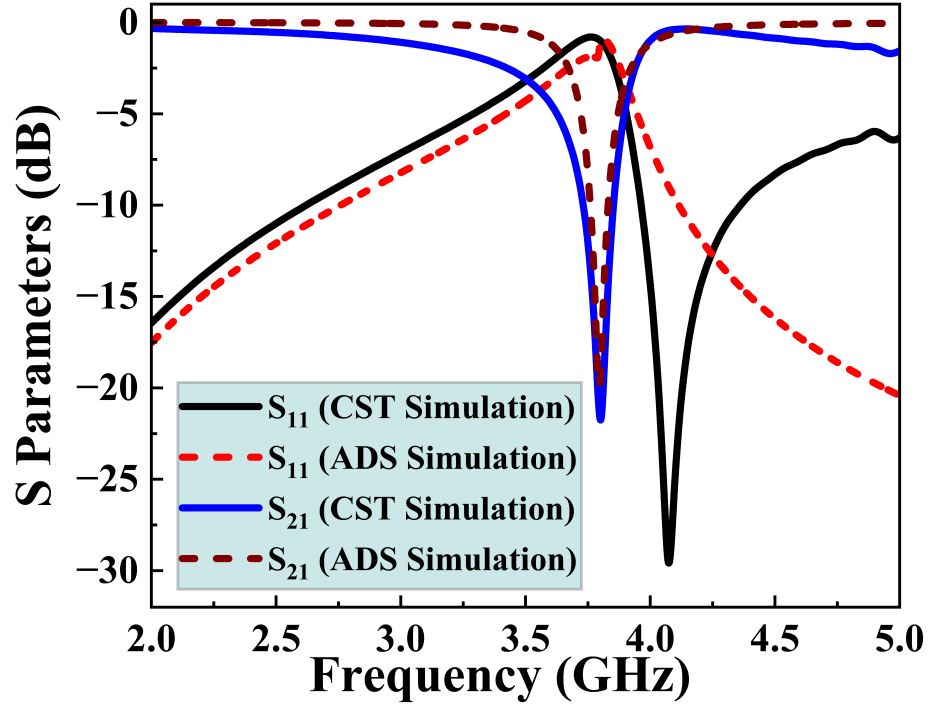


Figure 3.5: S Parameters using CST and ADS for the proposed sensor.

The validity of the equivalent circuit model was verified by comparing the S-parameter responses from CST and ADS (Fig. 3.5). As shown in the frequency response plots, the two models exhibit strong agreement, confirming that the lumped-element representation accurately captures the resonator's electromagnetic behavior.

Chapter 4

Experimental Analysis and Findings

The fabrication of the proposed sensor was carried out following the procedure reported by [32]. For completeness, the essential steps of the fabrication process are summarized in this section.

4.1 Fabrication Process of the CSMRR

The fabrication of the proposed sensor was carried out through a sequence of well-defined steps, starting with the preparation of the PCB layout and concluding with the final assembly of all components. A cost-effective PCB etching process was employed to realize the designed and optimized resonator structure (modeled using CST Microwave Studio) on an RT/duroid 5880 substrate ($\epsilon_r = 2.20$, $\tan \delta = 0.0009$, thickness = 1.575 mm), as illustrated in Figure 4.1.

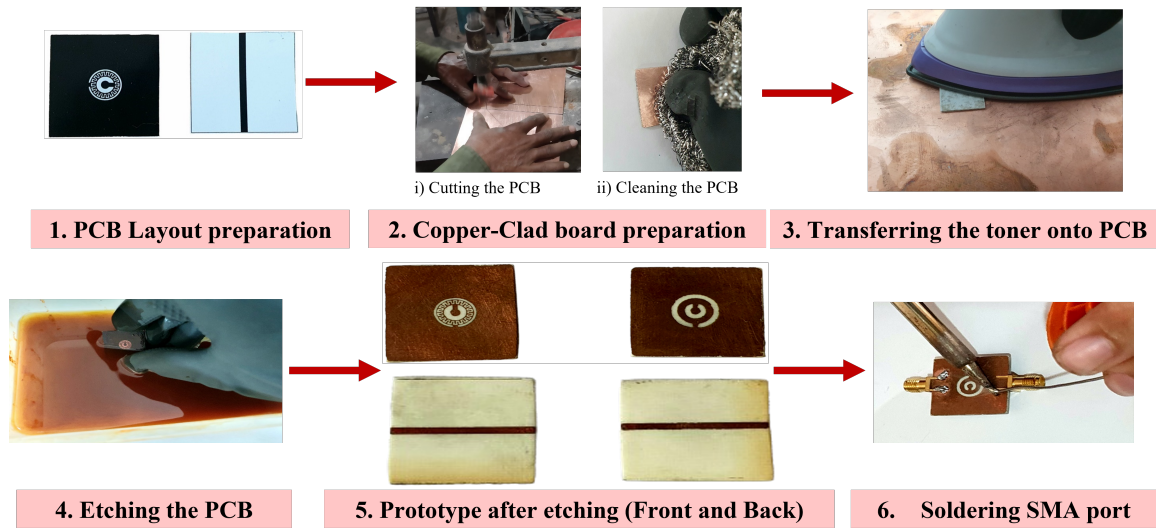


Figure 4.1: The step-by-step fabrication process from [32].

The following details each stage of the process:

4.1.1 PCB Layout Preparation

The first step involves creating the layout of the sensor. Using appropriate software such as CST Studio Suite, a DXF file of the design is exported by navigating to **Modeling >Exchange >Import/Export >Export >2D Files**. The exported DXF file is converted into a PCB layout using Adobe Illustrator. This layout will serve as the basis for the fabrication process.

4.1.2 Copper-Clad Board Preparation

Once the layout is finalized, a copper-clad board is prepared. The copper board is cut to the appropriate size using a cutting tool to match the sensor layout. The copper surface is then cleaned using steel wool or abrasive scrubs to remove any oxide layers or contaminants, ensuring proper adhesion of the toner in the subsequent step.

4.1.3 Transferring the Toner onto the PCB

A printout of the PCB layout is made using a laser printer on glossy paper. It is essential to ensure that a mirror image of the design is printed to guarantee accurate transfer. The glossy side of the paper is then placed face down on the cleaned copper board, and a heated iron is applied to transfer the toner from the paper to the board. The heat from the iron melts the toner, transferring the design to the copper surface.

4.1.4 Etching the PCB

After the toner transfer, the copper board is submerged in an etching solution, typically ferric chloride (FeCl_3). The etching removes the unwanted copper, leaving only the toner-protected areas intact, corresponding to the sensor's design. The board is periodically checked during etching to ensure all unwanted copper is removed. Once complete, the board is removed and rinsed with water.

4.1.5 Cleaning and Finalizing the PCB

Following the etching process, acetone is applied to the PCB to remove the toner, revealing the final copper pattern. This step ensures that the etched areas are clean and ready for further processing.

4.1.6 Soldering the SMA Port

In the final step, an SMA connector is soldered onto the PCB. The connector is placed at the designated port on the board and soldered carefully to ensure proper electrical contact and minimal signal loss. This step enables RF signal transmission during sensor testing and calibration.

4.2 Sensor Measurement and Results

4.2.1 Experimental Setup

The complete VNA-based measurement arrangement is shown in Fig. 4.2. The experimental characterization of the fabricated CSMRR sensor was performed using a portable VNA (Lite VNA 64) to measure the scattering parameters under different

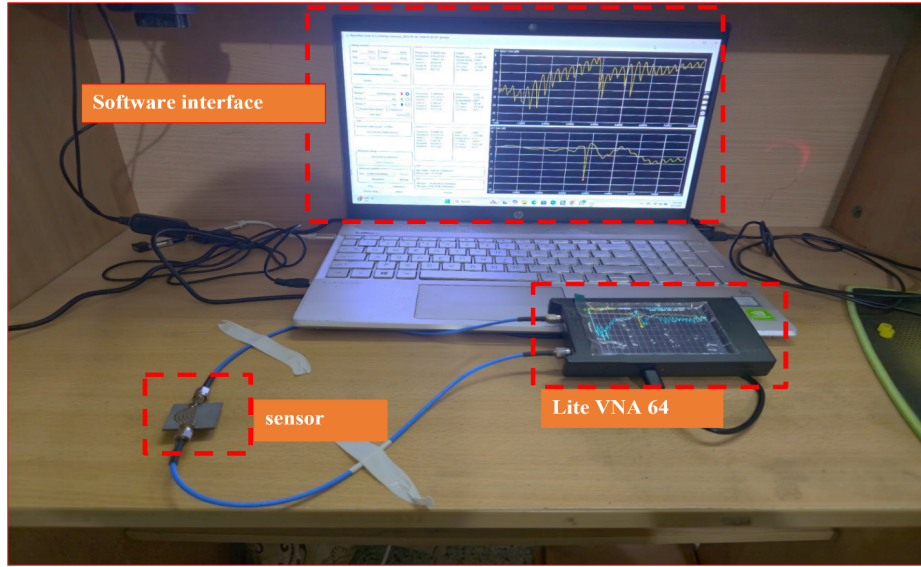


Figure 4.2: Measurement Setup with Lite VNA 64

loading conditions. The sensor was excited via a $50\ \Omega$ microstrip feedline, and two $50\ \Omega$ standard coaxial SMA connectors were used to interface the sensor with the measurement equipment.

Before measurement, a full two-port calibration was performed using the Short–Open–Load–Through (SOLT) technique to eliminate systematic errors introduced by cables and connectors. The calibration plane was set at the SMA connector reference to ensure accurate extraction of the sensor response.

A sample holder made of Polylactic acid (PLA) with a relative permittivity of 2.7 was used to apply the liquid samples. The sample holder was located at the highest electric-field region, as identified in the electromagnetic field analysis presented in Chapter 3. $40\ \mu\text{L}$ of liquid sample was poured into the sample holder using a micropipette to ensure a consistent sample volume and stable placement during measurement.

For each measurement, the sensor response was recorded over a frequency range that includes the unloaded resonance and the expected resonance shifts caused by liquid loading. After each measurement, the inner side of the sample holder was carefully cleaned with a cotton swab and dried to prevent cross-contamination between samples. The cleaning process caused an upshift of the notch frequency until it returned to the air values, which took about 30 seconds.

4.2.2 S-Parameter Results and Analysis

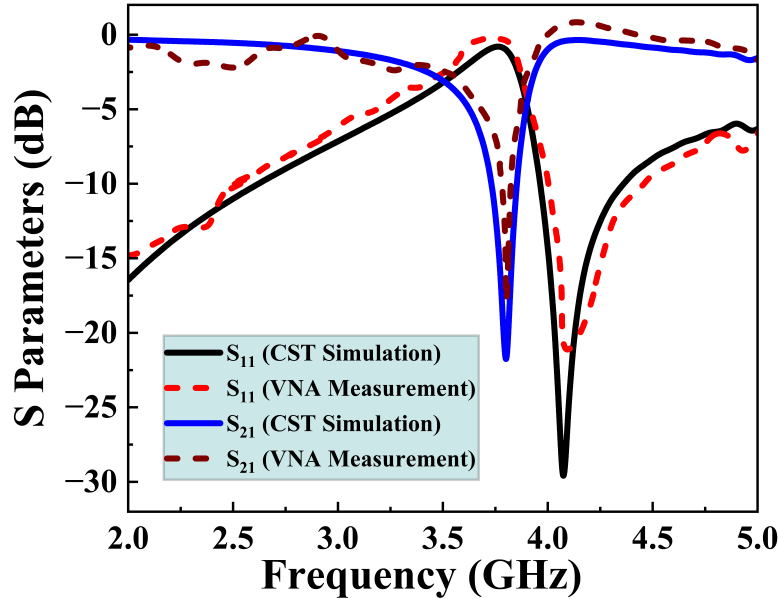


Figure 4.3: Comparison of S Parameters Between CST Simulation and VNA Measurement of the unloaded CSMRR sensor

The measured transmission coefficient (S_{21}) and reflection coefficient (S_{11}) of the unloaded sensor are shown in Figure 4.3. A distinct notch resonance is observed at approximately 3.8 GHz, which closely matches the simulated resonance obtained from CST Microwave Studio. Minor deviations between the simulated and measured results can be attributed to fabrication tolerances, connector losses, and variations in substrate parameters.

4.2.3 Implementation of the Sensor

The proposed CSMRR sensor offers a compact and planar solution for dielectric characterization of liquid samples. Due to its small footprint and simple fabrication process, the sensor can be easily integrated into portable microwave measurement systems. The requirement of only a minute volume of liquid makes the sensor suitable for applications where sample availability is limited, such as pharmaceutical quality assessment and chemical analysis. Additionally, operation within the

sub-6 GHz frequency range ensures compatibility with commonly available RF instrumentation. The stable and repeatable measurement response suggests that the sensor can be extended for real-time monitoring and mixture analysis with appropriate calibration models.

4.3 Analysis of the Mathematical Model

This section presents the empirical mathematical framework developed to extract the complex permittivity of ethanol–water mixtures using the proposed microwave sensor. The model is constructed exclusively using experimentally measured binary mixture data with ethanol concentrations ranging from 10% to 90%, while a 50% ethanol–water mixture is selected as the reference state. By correlating variations in resonant frequency and transmission coefficient with dielectric property variations, a robust first- and second-order matrix-based model is established.

The overall approach is consistent with resonance-based dielectric characterization methods used in CSRR-based microwave liquid sensors, where the frequency shift and transmission response are employed to estimate complex permittivity [33].

4.3.1 Physical Basis and Mathematical Modeling Strategy

When an ethanol–water mixture is introduced into the sensing region, the liquid perturbs the electromagnetic field distribution around the resonator. This perturbation changes the effective permittivity in the sensing volume and leads to: (i) a shift in the notch frequency, and (ii) a change in the attenuation depth at notch frequency, typically observed in $|S_{21}|$.

The dielectric behavior of polar liquids such as ethanol–water mixtures at microwave frequencies is governed by dipolar relaxation and can be described using the Debye model [34]. The complex permittivity is defined as

$$\varepsilon^*(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega), \quad (4.1)$$

where:

- $\varepsilon'(\omega)$ is the real part of permittivity, representing the ability of the medium to store electric energy;

- $\varepsilon''(\omega)$ is the imaginary part of permittivity, representing dielectric loss (energy dissipation);
- $j = \sqrt{-1}$ is the imaginary unit;
- $\omega = 2\pi f$ is the angular frequency (rad/s), and f is the frequency (Hz).

In the Debye formulation,

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 - j\omega\tau}, \quad (4.2)$$

where:

- ε_s is the static (low-frequency) permittivity;
- ε_∞ is the high-frequency permittivity limit;
- τ is the relaxation time constant (s), characterizing dipole reorientation speed.

Since the proposed sensor operates over a narrow band around its resonance, dispersion within the measurement bandwidth is small. Therefore, the complex permittivity can be treated as approximately constant around the operating frequency, allowing an empirical mapping between measured resonance quantities and $(\varepsilon', \varepsilon'')$.

4.3.2 Reference-Based Variations

To reduce systematic offsets and improve repeatability, all measurements are defined relative to a reference mixture (chosen as the 50% ethanol–water mixture). The measured response variations are defined as

$$\Delta f_0 = f_{0,\text{sam}} - f_{0,\text{ref}}, \quad (4.3)$$

$$\Delta S_{21} = S_{21,\text{sam}} - S_{21,\text{ref}}, \quad (4.4)$$

where:

- $f_{0,\text{sam}}$ is the resonance frequency of the unknown sample (Hz);
- $f_{0,\text{ref}}$ is the resonance frequency of the reference mixture (Hz);

- $S_{21,\text{sam}}$ is the transmission coefficient magnitude (or notch depth) at/near resonance for the sample (typically in dB);
- $S_{21,\text{ref}}$ is the transmission coefficient magnitude at/near resonance for the reference mixture.

In this work, S_{21} is used as the loss-related observable instead of the Q -factor to avoid bandwidth estimation uncertainty and because $|S_{21}|$ is directly obtained from the measured transmission response.

Dielectric property variations are defined as

$$\Delta\epsilon' = \epsilon'_{\text{sam}} - \epsilon'_{\text{ref}}, \quad (4.5)$$

$$\Delta\epsilon'' = \epsilon''_{\text{sam}} - \epsilon''_{\text{ref}}, \quad (4.6)$$

where $(\epsilon'_{\text{ref}}, \epsilon''_{\text{ref}})$ denote the known complex permittivity components of the reference mixture.

4.3.3 Linear Matrix Model (First-Order Approximation)

For small perturbations around the reference state, a first-order approximation is used:

$$\Delta f_0 = m_{11}\Delta\epsilon' + m_{12}\Delta\epsilon'', \quad (4.7)$$

$$\Delta S_{21} = m_{21}\Delta\epsilon' + m_{22}\Delta\epsilon''. \quad (4.8)$$

Here m_{ij} are empirical coefficients determined from calibration measurements; physically, they represent the sensitivity of Δf_0 and ΔS_{21} to changes in $\Delta\epsilon'$ and $\Delta\epsilon''$.

In compact matrix form,

$$\begin{bmatrix} \Delta f_0 \\ \Delta S_{21} \end{bmatrix} = \mathbf{A}_1 \begin{bmatrix} \Delta\epsilon' \\ \Delta\epsilon'' \end{bmatrix}, \quad (4.9)$$

with

$$\mathbf{A}_1 = \begin{bmatrix} -0.0313 & 0.2636 \\ 0.2071 & -2.6746 \end{bmatrix}. \quad (4.10)$$

The coefficients in $\mathbf{A}_1$ were obtained using least-squares regression from the experimentally measured ethanol–water dataset covering 10%–90% concentration levels (with 50% as reference).

4.3.4 Quadratic Matrix Model (Second-Order Approximation)

Over a wider concentration range, the sensor response becomes nonlinear due to stronger field–matter interaction and changes in dielectric loss. Therefore, the model is extended to include second-order terms:

$$\begin{bmatrix} \Delta f_0 \\ \Delta S_{21} \end{bmatrix} = \mathbf{A}_1 \begin{bmatrix} \Delta \varepsilon' \\ \Delta \varepsilon'' \end{bmatrix} + \mathbf{B}_2 \begin{bmatrix} (\Delta \varepsilon')^2 \\ \Delta \varepsilon' \Delta \varepsilon'' \\ (\Delta \varepsilon'')^2 \end{bmatrix}. \quad (4.11)$$

Here:

- $(\Delta \varepsilon')^2$ captures nonlinear effects associated with the real part of permittivity;
- $(\Delta \varepsilon'')^2$ captures nonlinear loss-related effects;
- $\Delta \varepsilon' \Delta \varepsilon''$ represents coupling between storage and loss mechanisms.

The quadratic coefficient matrix obtained from empirical fitting is

$$\mathbf{B}_2 = \begin{bmatrix} 0.0025 & 0.0034 & 0.0017 \\ -0.0309 & -0.0410 & 0.0028 \end{bmatrix}. \quad (4.12)$$

The quadratic feature matrix was verified to be full rank (rank = 5), which confirms that the selected quadratic basis is identifiable and does not introduce linear dependence among features.

4.3.5 Inverse Formulation for Permittivity Extraction

To estimate $(\Delta \varepsilon', \Delta \varepsilon'')$ from measured $(\Delta f_0, \Delta S_{21})$, the inverse of the first-order matrix is used:

$$\mathbf{A}_1^{-1} = \begin{bmatrix} -91.6418 & -9.0317 \\ -7.0972 & -1.0734 \end{bmatrix}. \quad (4.13)$$

Rearranging the quadratic model yields the implicit inverse form:

$$\begin{bmatrix} \Delta \varepsilon' \\ \Delta \varepsilon'' \end{bmatrix} = \mathbf{A}_1^{-1} \left(\begin{bmatrix} \Delta f_0 \\ \Delta S_{21} \end{bmatrix} - \mathbf{B}_2 \begin{bmatrix} (\Delta \varepsilon')^2 \\ \Delta \varepsilon' \Delta \varepsilon'' \\ (\Delta \varepsilon'')^2 \end{bmatrix} \right). \quad (4.14)$$

Because $\Delta \varepsilon'$ and $\Delta \varepsilon''$ appear on both sides, the solution is obtained iteratively, starting from the linear estimate as an initial guess.

Finally, the absolute complex permittivity of the unknown sample is computed as

$$\varepsilon'_{\text{sam}} = \varepsilon'_{\text{ref}} + \Delta \varepsilon', \quad (4.15)$$

$$\varepsilon''_{\text{sam}} = \varepsilon''_{\text{ref}} + \Delta \varepsilon''. \quad (4.16)$$

4.3.6 Sensitivity Analysis

The frequency-based sensitivity of the sensor is defined as the normalized resonance shift caused by a one-unit change in relative permittivity:

$$S_{\varepsilon_r} = \left| \frac{f_{\text{sam}} - f_{\text{empty}}}{f_{\text{empty}}(\varepsilon_r - 1)} \right| \times 100, \quad (4.17)$$

where:

- S_{ε_r} is the sensitivity expressed in percent (%);
- f_{empty} is the resonance frequency (Hz) when the microchannel is empty (typically air-filled);
- f_{sam} is the resonance frequency (Hz) when the channel is filled with the sample under test;
- ε_r is the relative permittivity (dielectric constant) of the sample (dimensionless).

The numerator $|f_{\text{sam}} - f_{\text{empty}}|$ represents the absolute frequency shift due to loading, while the denominator normalizes this shift by the baseline frequency and the permittivity contrast $(\varepsilon_r - 1)$, enabling fair comparison across different liquids.

4.3.7 Error Analysis: Average Error and Standard Deviation

To quantify model accuracy, the extracted permittivity values are compared with Literature values. Let $\varepsilon_{\text{ext},i}$ denote an extracted value (either ε' or ε'') for the i -th test case, and $\varepsilon_{\text{ref},i}$ the corresponding Literature value. For N test cases, the average error is defined as:

$$\text{Average Error} = \frac{1}{N} \sum_{i=1}^N |\varepsilon_{\text{ext},i} - \varepsilon_{\text{ref},i}| \quad (4.18)$$

and the standard deviation is computed as:

$$\text{Standard Deviation} = \sqrt{\frac{1}{N} \sum_{i=1}^N (\varepsilon_{\text{ext},i} - \varepsilon_{\text{ref},i})^2}. \quad (4.19)$$

These two metrics provide complementary accuracy measures: the average error reflects typical absolute deviation, while the standard deviation penalizes larger deviations more strongly and is therefore sensitive to outliers.

4.4 Calibration of the Sensor

This section presents the calibration procedure and performance evaluation of the proposed microwave sensor for extracting the complex permittivity of ethanol–water mixtures. The calibration is performed using experimentally measured transmission responses obtained from air, deionized (DI) water, pure ethanol, and ethanol–water binary mixtures with ethanol concentrations ranging from 10% to 90%.

4.4.1 Baseline Calibration Using Air, DI Water, and Pure Ethanol

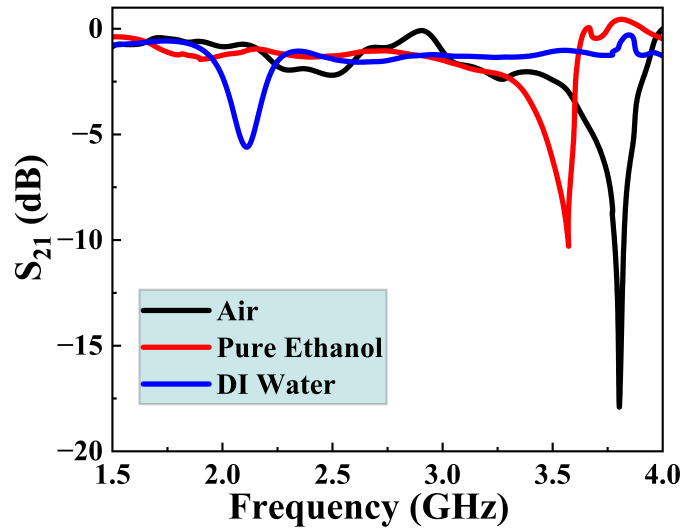


Figure 4.4: Measured transmission coefficient (S_{21}) responses of the proposed sensor for Common Solvents (DI water and Pure ethanol) compared with air (unloaded) response.

Figure 4.4 illustrates the measured S_{21} responses of the proposed sensor for air, DI water, and pure ethanol in the sample holder. These three materials represent distinct dielectric extremes within the sensing range. Air exhibits the highest resonance frequency and minimal attenuation due to its low permittivity and negligible dielectric loss. In contrast, DI water produces a pronounced downward shift in resonance frequency and significant attenuation, reflecting its high real and

imaginary permittivity. Pure ethanol shows an intermediate response between air and DI water.

These baseline measurements establish the sensor's dynamic operating range and confirm that both the resonance frequency shift (Δf_0) and the transmission magnitude variation (ΔS_{21}) are highly sensitive to dielectric loading. Furthermore, this figure validates the suitability of using S_{21} as a loss-related observable for calibration and permittivity extraction.

4.4.2 Calibration Using Ethanol-Water Binary Mixtures for the Mathematical Model

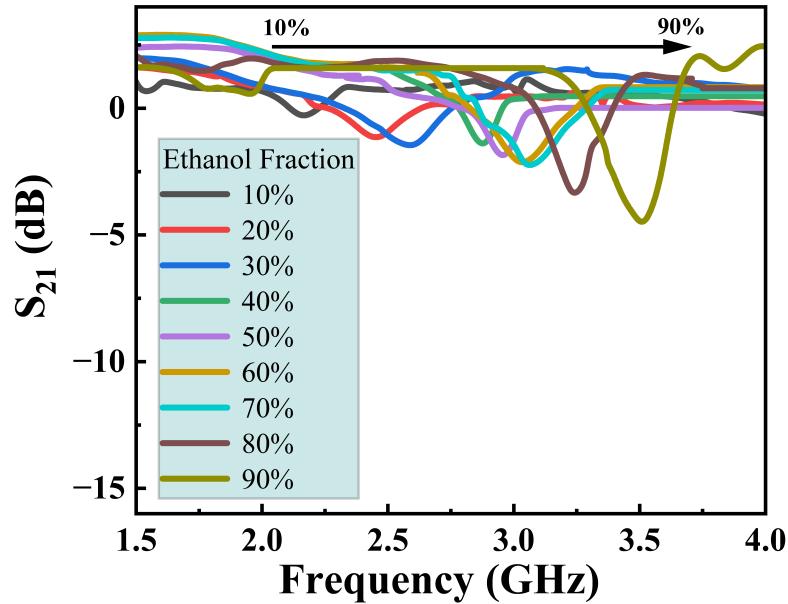


Figure 4.5: Measured transmission coefficient (S_{21}) for ethanol–water binary mixtures with ethanol concentrations ranging from 10% to 90%.

Figure 4.5 shows the measured transmission responses for ethanol–water binary mixtures with ethanol volume fractions varying from 10% to 90%. As the ethanol concentration increases, the resonance frequency gradually shifts to higher values, indicating a decrease in the effective real permittivity of the mixture. At the same time, the attenuation depth varies nonlinearly with changes in dielectric loss. The

nonlinear variation of both resonance frequency and attenuation depth across the full concentration range motivates the use of a quadratic mathematical model for calibration. Accordingly, the complete 10% to 90% data is used as the empirical basis for estimating the coefficients of the proposed quadratic matrix model.

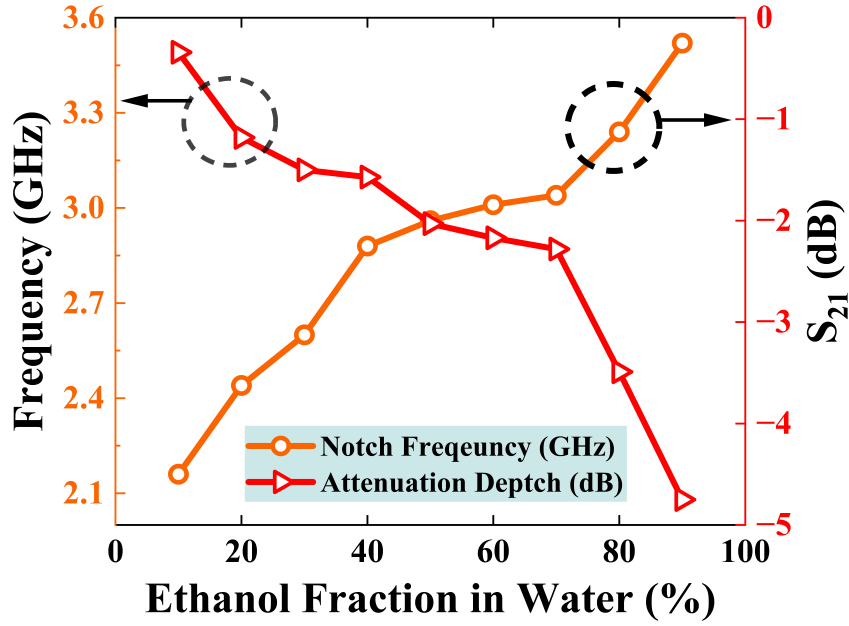


Figure 4.6: Variation of notch frequency and attenuation depth as a function of ethanol fraction in water.

Fig. 4.6 presents the extracted notch frequency and attenuation depth as functions of ethanol concentration. The notch frequency increases nonlinearly with ethanol fraction, while the attenuation depth exhibits a non-monotonic trend due to competing dielectric relaxation and loss mechanisms.

These extracted parameters form the two independent measured quantities, Δf_0 and ΔS_{21} , which are used as inputs to the quadratic model described.

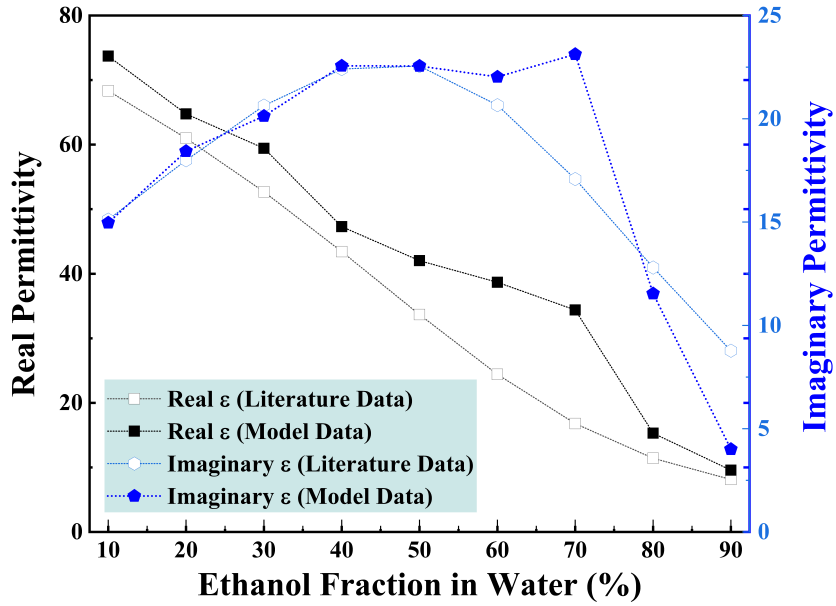


Figure 4.7: Comparison between the literature value of the relative permittivity and the ones calculated from the mathematical model.

Fig. 4.7 compares the real and imaginary parts of the complex permittivity extracted using the proposed quadratic model with corresponding literature values. The extracted real permittivity closely follows the decreasing trend reported in the literature as ethanol concentration increases. Similarly, the extracted imaginary permittivity captures the characteristic variation associated with dielectric loss behavior in ethanol-water mixtures. The strong agreement between extracted and reference values confirms the accuracy and reliability of the proposed calibration methodology.

4.5 Performance Analysis of the Sensor

Fig. 4.8 shows the variation of sensor sensitivity as a function of real permittivity (ϵ_r) ranging from 5 to 80. Higher sensitivity is observed at lower permittivity values, corresponding to higher ethanol concentrations. As the real permittivity increases, the sensitivity gradually decreases.

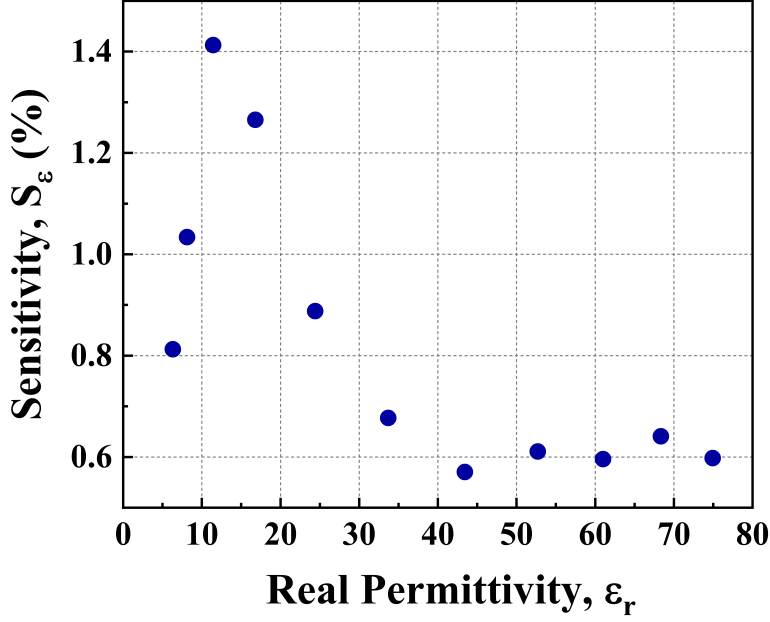


Figure 4.8: Comparison between the literature value of the relative permittivity and the ones calculated from the mathematical model.

Table 4.1 summarizes the percentage error statistics of the extracted complex permittivity. The low average errors and standard deviations indicate strong agreement between the proposed model and reference data across the full calibration range.

Table 4.1: Percentage error statistics of the extracted complex permittivity.

Metrics	Real Permittivity (ϵ')	Imaginary Permittivity (ϵ'')
Average Error (%)	2.11	0.80
Standard Deviation (%)	1.91	0.60

Finally, calibration is performed using air, DI water, pure ethanol, and ethanol-water binary mixtures spanning 10%- 90% concentration. Notch frequency shift and transmission attenuation are extracted and mapped to dielectric properties using an empirically derived quadratic matrix model. Validation against literature data, sensitivity analysis, and error statistics confirm the accuracy, robustness, and reliability of the proposed calibration methodology.

4.6 Comparison with other sensors

The proposed sensor is compared with recently reported microwave liquid characterization sensors in terms of average sensitivity, sample material, sensor type, and size, as summarized in Table 4.2.

Table 4.2: Comparison of the proposed CSMRR sensor with other works

Reference (Year)	Sample Material	Avg. Sens. (%)	Sensor Type	Size (mm $\times$ mm)
[18] , (2024)	Ethanol–water mixtures (10–90%)	0.78	Curved-groove CSRR	40 $\times$ 30
[19] , (2020)	Water–ethanol mixtures; methanol; butanol	$\approx$ 0.6	Multiple CSRR (MCSRR)	35 $\times$ 25
[20] , (2022)	Ethanol–water mixtures	0.041	Multi-element circular CSRR	28 $\times$ 20
[21] , (2019)	Water–ethanol; methanol; butanol	$\approx$ 0.3	Semi-lumped meander OCSRR	Compact chip
[23] , (2021)	Eight liquids (hexane–water)	0.87	Triple CSRR	75 $\times$ 40
[24] , (2022)	Water; methanol; ethanol; acetone; biological cells	Not reported	Interdigitated Capacitor (IDC)	14 $\times$ 16
[25] , (2023)	Ethanol; methanol; DI water	$\approx$ 0.9	Triple-ring CSRR	25 $\times$ 20
[26] , (2024)	Water–ethanol; water–glycerol mixtures	$\approx$ 0.5*	Modified SRR (M-SRR)	18 $\times$ 18
This work	Ethanol–water mixtures (10–90%)	0.892	Concentric Semi-Circular Multi-Ring Resonator (CSMRR)	26 $\times$ 28

Compared to the multiple complementary split-ring resonator (MCSRR) sensor reported in [19], which achieved an approximate sensitivity of 0.6% with a larger sensing area (35 mm $\times$ 25 mm), the proposed CSMRR demonstrates a noticeable improvement in sensitivity while maintaining a comparable physical size. This enhancement can be attributed to the stronger electric-field confinement produced by the concentric semi-circular multi-ring geometry, which increases the effective interaction volume between the electromagnetic fields and the liquid under test.

In contrast to the triple-ring CSRR presented in [25], which reported a sensitivity of approximately 0.9% using alcohol and deionized (DI) water samples with a

footprint of $25\text{ mm} \times 20\text{ mm}$, the proposed sensor achieves a comparable sensitivity while offering improved stability for binary mixture characterization, particularly in the ethanol–water concentration range. The semi-circular configuration further enhances field uniformity across the sensing region, thereby reducing measurement uncertainty associated with asymmetric sample loading.

The curved-groove CSRR reported in [18] achieved a sensitivity of 0.78% over ethanol–water mixtures but required a larger sensing area of $40\text{ mm} \times 30\text{ mm}$. The proposed CSMRR sensor surpasses this sensitivity while occupying approximately 39% less area, demonstrating its suitability for compact and portable sensing platforms.

Although the triple-CSRR configuration reported in [23] achieved a relatively high sensitivity of 0.87%, the design required a significantly larger footprint ($75\text{ mm} \times 40\text{ mm}$) and was validated across multiple liquids rather than being optimized for binary mixture discrimination. In comparison, the proposed work achieves slightly higher sensitivity with a substantially reduced sensor size, emphasizing its effectiveness for targeted liquid mixture analysis.

Voltage-based and broadband sensors, such as those presented in [26] and [24], offer alternative sensing modalities but lack the frequency-selective response required for precise mixture quantification. Consequently, their reported sensitivities are either lower or not directly comparable to resonant CSRR-based sensors.

Overall, the proposed CSMRR sensor demonstrates a favorable balance between high relative sensitivity (0.892%), compact size ($26\text{ mm} \times 28\text{ mm}$), and effective binary mixture discrimination, outperforming or matching state-of-the-art designs reported in the literature. These results confirm that the concentric semi-circular multi-ring architecture provides enhanced electromagnetic field localization and improved sensor–sample interaction, making it a strong candidate for high-precision liquid characterization applications.

Chapter 5

Conclusion and Future Scope

5.1 Future Prospects of the Proposed Sensor

While the proposed CSMRR-based microwave sensor has been validated under controlled laboratory conditions, several extensions can further enhance its applicability and robustness. Future work should investigate the influence of environmental parameters such as temperature, humidity, and variations in water composition on sensor performance. Incorporating environmental compensation techniques or adaptive calibration schemes would improve measurement reliability in practical deployment scenarios.

The compact planar design and sub-6 GHz operating frequency make the sensor appropriate for integration with wireless communication systems. Future work will focus on replacing the NanoVNA with a miniaturized, self-powered RF front end or software-defined radio (SDR) systems to create a fully embedded and autonomous platform. Such a compact system would enable real-time, remote monitoring and support field-deployable applications in environmental sensing, industrial process monitoring, and smart IoT platforms.

Furthermore, machine learning approaches can be explored to improve sensing accuracy and broaden functionality. Using key features such as notch frequency and S-parameter magnitude shifts as inputs, neural network models can be trained to directly predict pollutant concentration or complex permittivity, especially for complex or multicomponent liquid systems.

The proposed sensing architecture can also be extended to characterize other liquid materials, including biological fluids, transformer oil, and industrial chemicals. With suitable modifications to the sample holder or incorporation of microfluidic

channels, the sensor may be adapted for continuous-flow and real-time monitoring applications.

5.2 Conclusion

In this work, a compact Concentric Semi-Circular Multi-Ring Resonator (CSMRR)-based microwave sensor has been designed, fabricated, and experimentally validated for liquid dielectric characterization. The sensor operates at a 3.8 GHz notch resonance on an RT/duroid 5880 substrate, providing strong electric-field confinement and high sensitivity to dielectric perturbations induced by small liquid volumes. The design methodology combined full-wave electromagnetic simulation, equivalent circuit modeling, and experimental verification using vector network analyzer measurements. The sensor exhibited precise, repeatable resonance shifts when exposed to ethanol–water binary mixtures over a wide concentration range. An empirical quadratic calibration model was developed to extract complex permittivity, demonstrating good agreement with reported reference data. In addition, a comparison with the state-of-the-art recently reported microwave liquid sensors indicates that the proposed CSMRR design offers a competitive, compact, and verifiable size, and a high sensitivity over an extensive range of permittivity while using only a minimal amount of sample for testing. The requirement for only a minute sample volume and the use of simple PCB fabrication techniques further highlight its suitability for low-cost, portable sensing applications.

Overall, the proposed CSMRR-based sensor represents a reliable and scalable platform for liquid dielectric characterization and provides a strong foundation for future development toward wireless, intelligent, and field-deployable microwave sensing systems.

Bibliography

- [1] X. Chen, W. Chen, X. Zhang, D. Cheng, and Y. Ren, "The study on the dielectric properties of structural changes of surfactant aqueous solution by molecular dynamics simulation," *J. Mol. Liq.*, vol. 379, no. 121622, p. 121622, Jun. 2023.
- [2] P. Mester, M. Wagner, and P. Rossmanith, "Antimicrobial effects of short chained imidazolium-based ionic liquids—influence of anion chaotropicity," *Ecotoxicol. Environ. Saf.*, vol. 111, pp. 96–101, Jan. 2015.
- [3] D. El Khaled, N. N. Castellano, J. A. Gázquez, A.-J. Perea-Moreno, and F. Manzano-Agugliaro, "Dielectric spectroscopy in biomaterials: Agrophysics," *Materials (Basel)*, vol. 9, no. 5, p. 310, Apr. 2016.
- [4] A. La Gioia, E. Porter, I. Merunka, A. Shahzad, S. Salahuddin, M. Jones, and M. O'Halloran, "Open-ended coaxial probe technique for dielectric measurement of biological tissues: Challenges and common practices," *Diagnostics (Basel)*, vol. 8, no. 2, p. 40, Jun. 2018.
- [5] P. Mester, M. Wagner, and P. Rossmanith, "Antimicrobial effects of short chained imidazolium-based ionic liquids—influence of anion chaotropicity," *Ecotoxicol. Environ. Saf.*, vol. 111, pp. 96–101, Jan. 2015.
- [6] K. C. Ghanakota, Y. R. Yadam, S. Ramanujan, V. P. V., and K. Arunachalam, "Study of ultra high frequency measurement techniques for online monitoring of partial discharges in high voltage systems," *IEEE Sens. J.*, vol. 22, no. 12, pp. 11 698–11 709, Jun. 2022.
- [7] N. Abd Rahman, Z. Zakaria, R. Abd Rahim, Y. Dasril, and A. A. Mohd Bahar, "Planar microwave sensors for accurate measurement of material characterization: A review," *TELKOMNIKA*, vol. 15, no. 3, p. 1108, Sep. 2017.

- [8] L. Wang, "Microwave sensors for breast cancer detection," *Sensors (Basel)*, vol. 18, no. 2, p. 655, Feb. 2018.
- [9] S. A. Wani, R. Sarathi, and V. Subramanian, "A multivariable sensing system for condition monitoring of oil-immersed transformers," *IEEE Sens. J.*, vol. 25, no. 6, pp. 9708–9717, Mar. 2025.
- [10] S. Harnsoongnoen, "Microwave sensors based on coplanar waveguide loaded with split ring resonators: A review," *j.ijast*, vol. 12, no. 4, Nov. 2018.
- [11] M. A. Khalil, W. H. Yong, T. Batool, A. Hoque, L. Y. Chiong, H. H. Goh, T. A. Kurniawan, M. S. Soliman, and M. T. Islam, "Highly sensitive split ring resonator-based sensor for quality monitoring of edible oils," *Sci. Rep.*, vol. 15, no. 1, p. 2283, Jan. 2025.
- [12] A. J. A. Al-Gburi, Z. Zakaria, N. A. Rahman, A. A. Althwayb, I. M. Ibrahim, T. Saeidi, Z. A. Dayo, and S. Ahmad, "A miniaturized and highly sensitive microwave sensor based on CSRR for characterization of liquid materials," *Materials (Basel)*, vol. 16, no. 9, p. 3416, Apr. 2023.
- [13] E. L. Chuma, Y. Iano, G. Fontgalland, and L. L. Bravo Roger, "Microwave sensor for liquid dielectric characterization based on metamaterial complementary split ring resonator," *IEEE Sens. J.*, vol. 18, no. 24, pp. 9978–9983, Dec. 2018.
- [14] Growth Market Reports. (2024) Microwave sensors market. [Online]. Available: <https://growthmarketreports.com/report/microwave-sensors-market>
- [15] Precedence Research. (2025) Microwave devices market size to worth usd 14.89 billion by 2034. [Online]. Available: <https://www.precedenceresearch.com/microwave-devices-market>
- [16] RoboticsBD. (2025) 10.525 ghz hb100x microwave sensor module. [Online]. Available: <https://store.roboticsbd.com/motion-sensor-robotics-bangladesh/2221-10525ghz-hb100x-microwave-sensor-module-robotics-bangladesh.html>
- [17] Verified Market Research. (2025) Global microwave flow sensor market. [Online]. Available: <https://www.verifiedmarketresearch.com/reports/?key=Global+Microwave+Flow+Sensor+Market>

- [18] X. Han, K. Liu, S. Zhang, P. Peng, C. Fu, L. Qiao, and Z. Ma, "CSRR metamaterial microwave sensor for measuring dielectric constants of solids and liquids," *IEEE Sens. J.*, vol. 24, no. 9, pp. 14 167–14 176, May 2024.
- [19] A. Javed, A. Arif, M. Zubair, M. Q. Mehmood, and K. Riaz, "A low-cost multiple complementary split-ring resonator-based microwave sensor for contactless dielectric characterization of liquids," *IEEE Sens. J.*, vol. 20, no. 19, pp. 11 326–11 334, Oct. 2020.
- [20] C. Wang, X. Liu, Z. Huang, S. Yu, X. Yang, and X. Shang, "A sensor for characterisation of liquid materials with high permittivity and high dielectric loss," *Sensors (Basel)*, vol. 22, no. 5, p. 1764, Feb. 2022.
- [21] C.-S. Lee, B. Bai, Q.-R. Song, Z.-Q. Wang, and G.-F. Li, "Open complementary split-ring resonator sensor for dropping-based liquid dielectric characterization," *IEEE Sens. J.*, vol. 19, no. 24, pp. 11 880–11 890, Dec. 2019.
- [22] W. Liu, H. Sun, and L. Xu, "A microwave method for dielectric characterization measurement of small liquids using a metamaterial-based sensor," *Sensors (Basel)*, vol. 18, no. 5, p. 1438, May 2018.
- [23] A. Buragohain, A. T. T. Mostako, and G. S. Das, "Low-cost CSRR based sensor for determination of dielectric constant of liquid samples," *IEEE Sens. J.*, vol. 21, no. 24, pp. 27 450–27 457, Dec. 2021.
- [24] H. Mariam, P. Poulichet, H. Takhedmit, F. Deshours, E. Richalot, and O. Francais, "Accurate characterization by dielectric spectroscopy up to 25 GHz of nano-liter range liquid volume within a microfluidic channel," *IEEE Sens. J.*, vol. 22, no. 4, pp. 3553–3564, Feb. 2022.
- [25] A. J. A. Al-Gburi, Z. Zakaria, N. A. Rahman, A. A. Althwayb, I. M. Ibrahim, T. Saeidi, Z. A. Dayo, and S. Ahmad, "A miniaturized and highly sensitive microwave sensor based on CSRR for characterization of liquid materials," *Materials (Basel)*, vol. 16, no. 9, p. 3416, Apr. 2023.
- [26] W.-J. Wu, H. Xie, W.-S. Zhao, and W. Wang, "A microwave sensor system based on M-SRRs for assessing the complex permittivity of liquid samples," *IEEE Sens. J.*, vol. 24, no. 24, pp. 40 827–40 838, Dec. 2024.

- [27] P. Velez, J. Munoz-Enano, A. Ebrahimi, C. Herrojo, F. Paredes, J. Scott, K. Ghorbani, and F. Martin, "Single-frequency amplitude-modulation sensor for dielectric characterization of solids and microfluidics," *IEEE Sens. J.*, vol. 21, no. 10, pp. 12 189–12 201, May 2021.
- [28] A. Kundu, S. M. R. H. Shawon, S. Kapali, A. Helal, and K. Ali, "Hairpin resonator-based microwave sensor for detection of nitrogenous fertilizers in soil and water," *IEEE Sens. J.*, vol. 24, no. 17, pp. 27 436–27 445, Sep. 2024.
- [29] S. A. Alotaibi, Y. Cui, and M. M. Tentzeris, "CSRR based sensors for relative permittivity measurement with improved and uniform sensitivity throughout [0.9–10.9] GHz band," *IEEE Sens. J.*, vol. 20, no. 9, pp. 4667–4678, May 2020.
- [30] A. Ebrahimi, J. Scott, and K. Ghorbani, "Ultrahigh-sensitivity microwave sensor for microfluidic complex permittivity measurement," *IEEE Trans. Microw. Theory Tech.*, vol. 67, no. 10, pp. 4269–4277, Oct. 2019.
- [31] L.-H. Hsieh, "Analysis, modeling and simulation of ring resonators and their applications to filters and oscillators," Ph.D. Dissertation, Texas A&M University, College Station, TX, May 2004.
- [32] M. N. U. Tanim, S. M. R. H. Shawon, T. U. Rashid, and K. Ali, "Microwave-based detection of heavy metals in water using an interdigital electrode-integrated complementary split ring resonator sensor," *IEEE Microw. Wirel. Technol. Lett.*, vol. 35, no. 1, pp. 135–138, Jan. 2025.
- [33] X. Han, P. Peng, C. Fu, L. Qiao, Z. Ma, K. Liu, and S. Zhang, "Highly integrated improved hexagonal CSRR-based fluid sensor for complex dielectric parameter detection," *IEEE Sens. J.*, vol. 24, no. 13, pp. 20 559–20 570, Jul. 2024.
- [34] J.-Z. Bao, M. L. Swicord, and C. C. Davis, "Microwave dielectric characterization of binary mixtures of water, methanol, and ethanol," *J. Chem. Phys.*, vol. 104, no. 12, pp. 4441–4450, Mar. 1996.