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NOVEL MICROWAVE SENSOR FOR ENHANCED BIOCHEMICAL DETECTION AND PREDICTION THROUGH MACHINE LEARNING FOR INDUSTRIAL APPLICATIONS

G. Challa Ram[1]
M. Venkata Subbarao
K. Padma Satya Sri
Naveen Kumar Maurya
D. Ramesh Varma
M. Prema Kumar

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ABSTRACT

This paper presents a novel sensor design that incorporates a microstrip patch antenna accompanied by a ground plane integrating a complementary split-ring resonator (CSRR). Integration of a circular CSRR into the microchip antenna has the potential to significantly improve radiation characteristics. The designed sensor operates at a frequency of 2.45 GHz, achieving an attenuation level of -27 dB. This design proposes the sensor's potential to function as a highly sensitive sensor by utilizing changes in the dielectric constant of biological samples. The changing dielectric constant of the analyte induces a frequency shift, allowing for the identification of different materials. Additionally, various regression algorithms based on machine learning have been employed to accurately assess the analyte's dielectric constant by studying the sensor's frequency response. Performance analysis indicates that exponential regression outperforms other approaches, showcasing a minimal root mean squared error of 0.0013. Machine learning techniques bring about substantial enhancements in sensor performance, thereby creating pathways for sophisticated applications in biochemical sensing.

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1. INTRODUCTION

In recent times, there have been notable advancements in the field of biochemical sensing, driven by the increasing demand for precise, rapid, and non-intrusive detection methods across various domains, including healthcare, environmental monitoring, and food safety. Among the array of available sensor technologies, microwave sensors have emerged as a promising solution for biochemical sensing due to their distinctive capacity to investigate the molecular interactions and attributes of biological substances (Song et al., 2023), (Zhang et al., 2022). Microwave sensors function within the electromagnetic spectrum, typically operating at

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[1] Corresponding author: G. Challa Ram
Email: challaram.grandhi@svecw.edu.in

frequencies ranging from hundreds of megahertz (MHz) to tens of gigahertz (GHz). When interacting with biochemical samples, which can encompass liquids like ethanol, benzene and ethylene glycol, these sensors provide valuable insights into the dielectric properties, composition, and structural changes of these substances (Rydosz et al., 2018), (Wu et al., 2022), (Gao et al., 2022), (Putnik et al., 2015). This interaction is the foundation for creating susceptible and specific microwave sensors capable of identifying and quantifying a broad spectrum of biological samples.

The core principle underpinning microwave biochemical sensing involves the measurement of alterations in the propagation characteristics of microwave signals, including aspects such as reflection, transmission, and resonance, when they encounter the target sample. These modifications arise from variances in the sample's dielectric constant, conductivity, and other electromagnetic properties. By analyzing these changes, researchers and scientists can extract valuable information about essential parameters such as concentration, molecular weight, and structural conformation of the target analyte (Zhou et al., 2018), (Zarifi et al., 2015), (Mirzavand et al., 2017).

Microchip patch antennas play a crucial role in wireless communication due to their compact dimensions, ease of integration, and versatile capabilities (Shastry & Sankarasubramaniam, 2020), (Mok et al., 2013). These microchip patch antennas are known for their compactness, lightweight construction, and high efficiency. They are widely utilized in various wireless communication applications, including mobile devices, satellite communication, RFID (Radio Frequency Identification), and more (Behdad & Sarabandi, 2004), (Zhao et al., 2011). Their design and performance continuously evolve, driven by advancements in materials, fabrication techniques, and design algorithms, solidifying their pivotal role in modern wireless technology. The fundamental structure of a microchip patch antenna comprises three key elements: a radiating patch, a dielectric substrate, and a ground plane. The radiating patch typically takes the form of a metallic component, often square or rectangular, and is connected to the electronic circuit's feed line. The dielectric substrate is a supportive medium for the patch, isolating it from the ground plane. The ground plane acts as a point of reference for the antenna's radiation and aids in achieving proper impedance matching. The design of compact, low-profile antennas, including conductive patch antennas situated over substrates, has become indispensable to meet the requirements of smaller devices while ensuring dependable wireless communication.

A microchip patch antenna incorporating a complementary split ring resonator (CSRR) represents an inventive and compact device that amalgamates two pivotal components in contemporary wireless communication and microwave engineering (Caloz & Itoh, 2006), (Ramesh Varma et al., 2023). The inclusion of a CSRR on the ground plane of the patch antenna is designed to amplify the antenna's capabilities by harnessing the unique electromagnetic characteristics offered by CSRR. Patch antennas hold widespread utility across various wireless communication systems due to their attributes of being low-profile, lightweight, and facile to integrate. These antennas are composed of a metal patch situated on a dielectric substrate, proficiently emitting electromagnetic waves in a specific direction. Nonetheless, their performance can be susceptible to factors such as frequency, bandwidth, and radiation pattern.

Complementary split ring resonators (CSRRs) represent a unique category of metamaterial distinguished by their captivating electromagnetic properties. These structures are comprised of resonant components featuring split ring geometry, allowing them to manipulate the propagation of electromagnetic waves in unconventional manners. CSRRs are renowned for their capacity to demonstrate negative permeability or permittivity characteristics. When a CSRR is strategically incorporated with a patch antenna, it can be positioned on the substrate or ground plane of the antenna to effectively modify its electromagnetic attributes. The fusion of a microchip patch antenna and a CSRR marks a fascinating intersection of conventional antenna principles and cutting-edge metamaterial advancements. This blended configuration promises of surmount the limitations typically associated with standard patch antennas, thereby ushering in novel opportunities for sophisticated wireless communication systems within our ever-expanding interconnected global landscape (Ram et al., 2022). Microwave and THz circuitry, featuring filters, antennas, and absorbers, is essential for precise, non-invasive material sensing applications (Ram et al., 2022), (Maurya et al., 2023).

This paper introduces a patch antenna design that incorporates a circular CSRR in the ground plane and analyzes its characteristics. The intended application of this design is to serve as a highly sensitive sensor for sensing various liquid samples, including water, ethanol, ethylene glycol, and benzene. Additionally, the design is enhanced by applying ML regression methods like linear, exponential, and polynomial regression to predict the dielectric value of samples using their resonant frequencies (Farooq & Sazonov, 2016), (Su et al., 2010), (Islam & Banerjee, 2014), (Ngoune et al., 2022). These sensors find extensive applications in industries, environmental analysis, and safety measures. These sensors excel in liquid-level sensing, offering real-time data for substances like ethanol, water, and benzene in tanks or containers. Industries benefit from precise control and optimization of production processes, while environmental monitoring aids in pollution control and regulatory compliance. In sectors like oil and gas, microwave sensors detect hydrocarbons like benzene, ensuring safety and compliance. Moreover, they support chemical analysis, biomedical applications, food and beverage quality control, and agricultural operations by providing accurate measurements and enhancing safety protocols. Microwave sensors stand as versatile tools in diverse domains, enhancing efficiency and safety. In (Song et al., 2023) a metamaterial-based microwave sensor is designed to sense and detect ethanol. A microwave sensor of exceptional sensitivity with a commendable quality factor is presented in (Zhang et al., 2022) for the detection of ethanol concentration. In (Rydosz et al., 2018) a microwave sensor to detect acetone and ethanol is discussed. The novelty of this research lies in how ML-based techniques are adopted with the sensor measurements to achieve high accuracy in predicting the sample dielectric values.

The paper's organization is as follows: Section II discusses the analysis of the proposed sensor, Section III explores its sensing abilities, Section IV outlines the ML-based regression approach employed for predicting sample dielectric values, and Section V draws conclusions.

2. DESIGN OF SENSOR

In this paper, we have employed a circular CSRR. A microstrip antenna featuring a circular CSRR represents an innovative way to design antennas. It combines the unique electromagnetic characteristics of CSRRs with the patch antenna. The design configuration comprises three distinct layers. The top layer consists of a copper metal sheet serving as the metallic radiating patch with dimensions L_1 = 47 mm and W_1 = 38.5 mm and a thickness of 0.035 mm. In the middle layer, a substrate crafted from Rogers material RT5880 with dielectric constant value 2.2 provides support to the patch and exerts an influence on its properties. Finally, the bottom layer functions as a reflective ground plane, constructed from copper metal, and play a role in shaping the antenna's radiation pattern. An inset feed, as shown in Figure 1 is used to feed the design, and the dimensions of the feed line are L_2= 30 mm and W_2= 3.4 mm.

In our design concept, we've placed a circular CSRR on the ground plane. These complementary rings are etched on the ground plane with an outer ring radius (R_1) of 8 mm and an inner ring radius (R_2) of 4 mm. Each ring has a width of 2 mm. This particular CSRR is designed to create a strong electric field at a specific spot. Fluctuations in the tested sample's dielectric constant cause alterations in the electric field, consequently leading to a shift in the frequency response of the sensor. This unique property makes it suitable for use as a highly effective sensor. The top view and a ground plane featuring the CSRR are shown in Figure 1 and Figure 2, respectively.

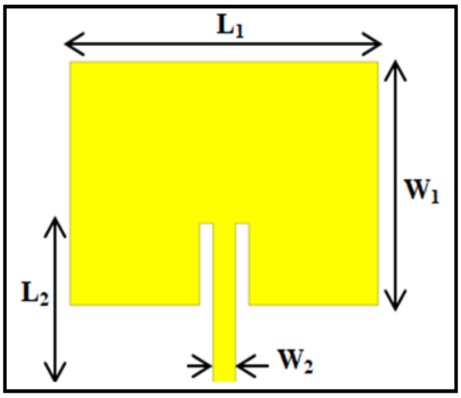

Figure 1. Top view of the proposed design

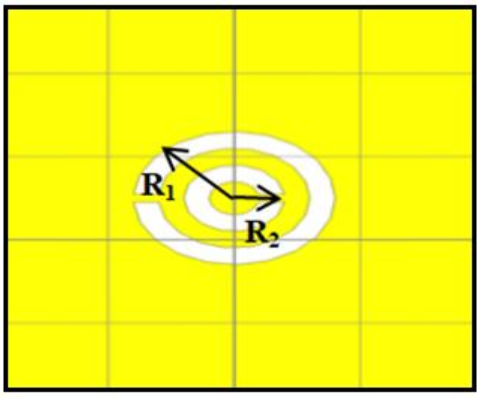

Figure 2. A Defective ground plane with CSRR

The proposed design is simulated using HFSS software. The reflection coefficient of the designed sensor is given in Figure 3. The designed sensor is simulating at a resonant frequency of 2.45 GHz with an attenuation of about -27 dB.

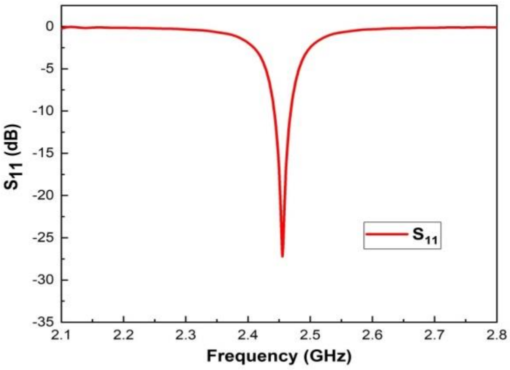

Figure 3. S_{11} response of the proposed design

Figure 4 illustrates the fabricated prototype of the designed sensor. The design is tested for S-parameters with Anritsu MS2037C VNA. Figure 5 depicts the simulated and measured results of the proposed design. From these results, it is evident that the measured and the simulated results have a close resemblance. These slight deviations are due to the losses incurred in the measurement.

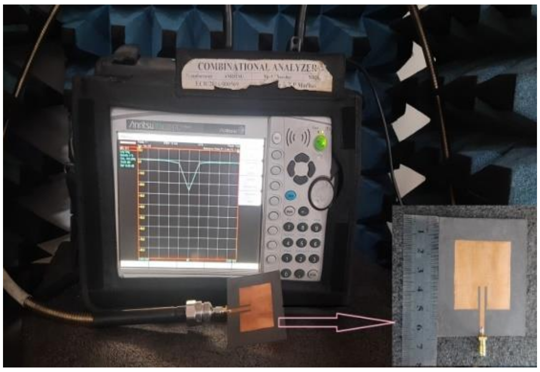

Figure 4. Measuring setup with fabricated design

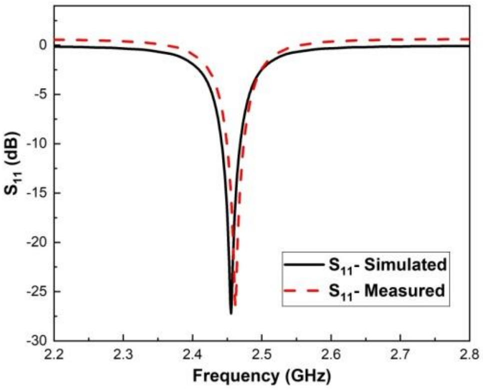

Figure 5. Measured Vs simulated response of the proposed design

3. PERFORMANCE ANALYSIS OF SENSOR

The proposed design functions as a sensor by positioning an analyte at a specific location over the CSRR on the ground plane, as shown in Figure 6. This region is susceptible to changes in analyte due to its high electric field concentration over the concentric split ring resonator. When the Analyte's dielectric constant is changed, it disrupts the electric field, leading to shifts in the frequency response.

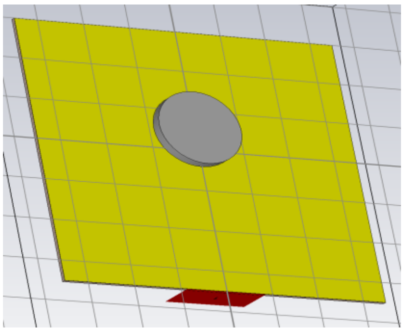

Figure 6. Sensor with sample under test

In the figure above, the circular grey disc represents the analyte under test. The proposed design resonates at a frequency of 2.45 GHz and can function as a sensor with high sensitivity to changes in analyte. A change in the analyte's dielectric value causes changes in the electric field, resulting in variations in the frequency response. In this specific design, when the analyte's dielectric value varies from 2 to 20, there is a noticeable frequency shift of approximately 0.14 GHz. This shift occurs from 2.46 GHz to 2.32 GHz, as shown in Figure 7. This frequency change serves as a reliable indicator of different materials based on their dielectric constants. The sensor sensitivity is given by the following equation.

$$S = \frac{\Delta f_r}{\Delta \varepsilon} \tag{1}$$

The proposed sensor has achieved a maximal sensitivity of 70 MHz/DU (Dielectric unit change).

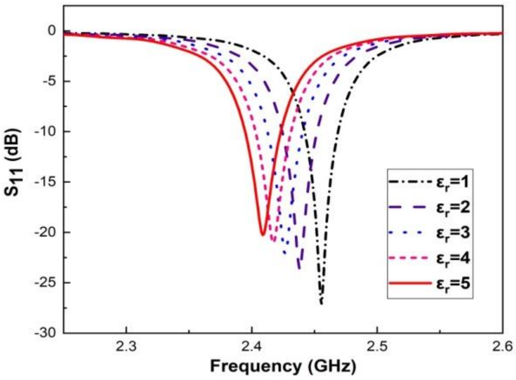

Figure 7. Frequency response of sensor for varying analyte

Further, the proposed sensor can detect various bio samples like ethanol, ethylene glycol, benzene and water. Figure 8 depicts the frequency response of the sensor for different bio-samples. As all the bio samples have different dielectric constant values, the proposed sensor could able to sense these bio samples with high precision. Table.1 illustrates the sensor's reaction to different biological samples. From these results it is evident that these liquid samples can be easily identified by the resonant frequency response of the proposed sensor.

Table 1. Sensor's response to biological samples

S. No	Analyte	Dielectric constant (ε)	Frequency (GHz)
1	Water	1.77	2.4418
2	Ethanol	1.84	2.4401
3	Ethylene Glycol	1.98	2.4387
4	Glycerine	2.16	2.4355
5	Benzene	2.25	2.4351

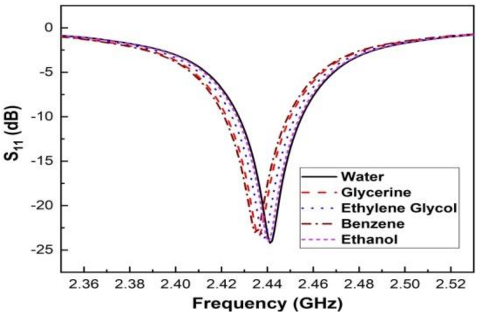

Figure 8. Sensor response for various bio samples

4. DIELECTRIC CONSTANT PREDICTION WTH ML BASED REGRESSION

Predicting the frequency response from the dielectric constant using regression models can be valuable in sensor design for several reasons. It can help in the design and optimization of sensors for specific applications. By predicting the frequency response, it can tailor sensor designs to maximize sensitivity and accuracy. Further it is also useful for the identification of the right material for designing the sensor. Predictive models can aid in material selection by predicting the relation between the dielectric constant of the material and the sensor's behavior. In applications where power consumption is critical (e.g., IoT devices or battery-powered sensors), optimizing the sensor's frequency response can help reduce energy consumption by ensuring that the sensor operates efficiently.

Machine learning based Regression techniques are employed in order to estimate the dielectric value of the sample (Ngoune et al., 2022). In these regression models, the response of the sensor is utilized to obtain the corresponding dielectric value of the sample. In this paper, several regression models are investigated in order to estimate the dielectric value of the sample with minimal error. This paper explores several regression models, including the linear regression model, polynomial regression model, and exponential regression model. The performance evaluation of the regression models are given by

$$MSE = \frac{1}{n}\sum_{j=1}^{n}\left(y_j - x_j\right)^2 \qquad (2)$$

$$RMSE = \sqrt{MSE}\sum_{j=1}^{n}\left(y_j - x_j\right)^2 \qquad (3)$$

$$R^2\ Error = 1 - \frac{MSE}{MSE(base\ line\ model)} \qquad (4)$$

4.1 Linear regression model

A core statistical technique, the linear regression model, serves to analyze the connection between variables (Farooq & Sazonov 2016). Its goal is to create a linear equation that optimally fits the data, enabling comprehension and prediction of how one variable changes in correspondence to alterations in other variables (referred to as the independent variables). Figure 9 depicts the resonant frequency versus dielectric constant and curve fitting plot. The empirical formulae to estimate the dielectric value of unknown sample using linear regression is given by

$$f = -0.006099x + 2.443 \qquad (5)$$

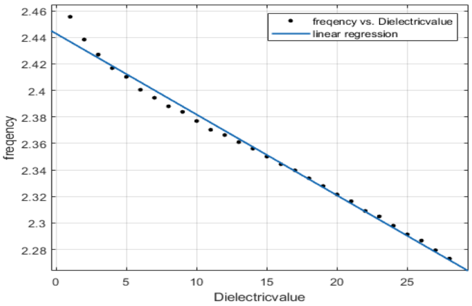

Figure 9. Relation between dielectric value and frequency using linear regression

4.2 Polynomial regression model

The polynomial regression model, as described by (Su et al., 2010), extends beyond linear regression by handling non-linear associations among variables. Unlike fitting only a straight line, it uses polynomial functions to capture curve-shaped patterns in datasets. This method's flexibility in modeling complex relationships renders it a versatile tool for prediction and data analysis. The following Figure 10 depicts the resonant frequency versus dielectric constant and curve fitting plot. The empirical formulae to estimate the dielectric constant of an unknown sample using polynomial regression is given by

$$f = (4.922 \times 10^{-5}) \times x^2 + (-0.007526) \times x^3 + 2.45 \qquad (6)$$

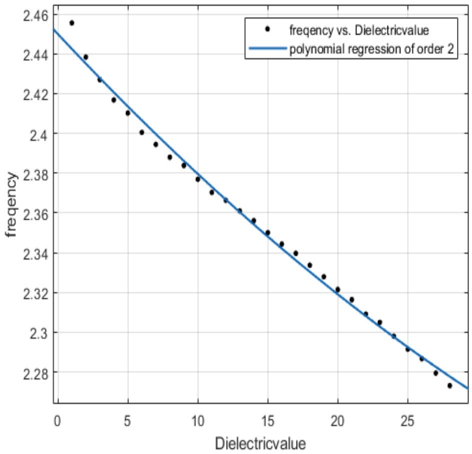

Figure 10. Relation between dielectric value and frequency using polynomial regression model

4.3 Exponential regression model

Exponential regression models are used to analyze data with exponential growth or decay patterns, making them valuable for understanding and predicting phenomena where values change rapidly at a consistent percentage rate over time or with changing inputs (Islam & Banerjee, 2014). Figure 11 depicts the resonant frequency versus dielectric constant and curve fitting diagram. The empirical formulae to estimate the dielectric value of an unknown sample using exponential regression is given by

$$f = 0.04655 \times e^{-0.6143x} + 2.436 \times e^{-0.002435x} \quad (7)$$

Table 2. Performance comparison of regression algorithms

Regression method	**RMSE**	**R-Square Error**
Linear	0.0049757	0.9906
Polynomial	0.0040670	0.9940
Exponential	0.0013720	0.9993

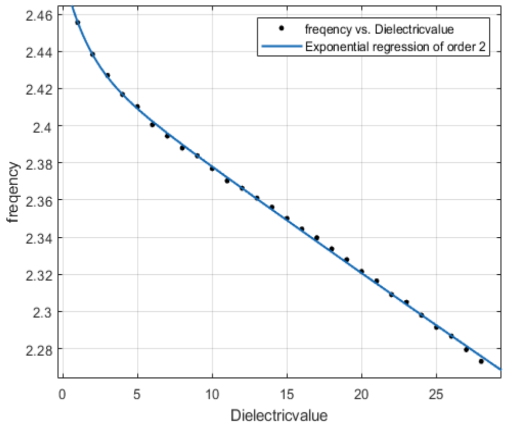

Figure 11. Relation between dielectric value and frequency using the exponential regression model

The Root Mean Square error (RMSE) and R-Square Error (R^2) for various regressions like linear, polynomial and exponential are tabulated in Table. 2. From the results, it is observed that the exponential regression outperforms linear and polynomial regression techniques. By employing the exponential regression the proposed sensor can predict the dielectric constant of the sample with RMSE value of 0.00137.

5. CONCLUSION

A Novel sensor is designed that amalgamates a microstrip patch with etched CSRR on the ground plane operating at 2.45 GHz with an attenuation level of -27 dB. This design underscores the sensor's potential to operate as a highly sensitive detector by leveraging the variations in the dielectric constant of biological samples. The ability of the analyte's changing dielectric constant to induce a frequency shift opens up avenues for identifying diverse materials based on their dielectric constants. Moreover, the utilization of various regression algorithms based on Machine Learning allows for an effective prediction of the analyte's dielectric constant using the frequency response of the designed sensor. Performance analysis underscores the superiority of exponential regression, demonstrating a minimal root mean squared error of 0.0013. These machine learning-driven approaches substantially augment the sensor's performance, paving the way for advanced applications in biochemical sensing. The findings of this study provide valuable insights into the potential of integrating machine learning techniques in sensor design for enhanced functionality and applicability in the field of biochemical sensing.

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G. Challa Ram
Department of ECE
Shri Vishnu Engineering College for Women, Bhimavaram, India.
challaram.grandhi@svecw.edu.in
ORCID 0000-0002-3790-1318

M. Venkata Subbarao
Department of ECE,
Shri Vishnu Engineering College for Women, Bhimavaram, India.
mvsubbarao@svecw.edu.in
ORCID 0000-0001-5840-2190

K. Padma Satya Sri
Department of ECE
Shri Vishnu Engineering College for Women, Bhimavaram, India.
satyasrikomatlapalli11@gmail.com
ORCID 0009-0006-0329-0746

Naveen Kumar Maurya
Department of ECE,
Vishnu Institute of Technology
Bhimavaram, India
Naveen.maurya222@gmail.com
ORCID 0000-0001-8006-3316

D. Ramesh Varma
Department of ECE,
Shri Vishnu Engineering College for Women, Bhimavaram, India
varmaramesh422@gmail.com
ORCID 0000-0002-9517-4964

M. Prema Kumar
Department of ECE,
Shri Vishnu Engineering College for Women, Bhimavaram, India
medapatipremkumar@gmail.com
ORCID 0000-0002-8702-8828