Vol 6 No 2 (2024) *e*-ISSN: 2682-8383

# Journal of Engineering Technology and Applied Physics

# Microwave Sensor for Sodium Chloride Density Measurement in Aqueous Solutions

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https://doi.org/10.33093/jetap.2024.6.2.8
*Manuscript Received: 7 March 2024, Accepted: 2 April 2024, Published: 15 September 2024*

***Abstract* — Accurate determination of sodium chloride (NaCl) density in water is vital for assessing environmental impact, preventing soil salinization in agriculture, ensuring quality and consistency in industrial processes, facilitating medical treatments, and maintaining taste and preservation standards in the food and beverage industry. This paper introduces a novel microwave sensor design specifically tailored to accurately assess NaCl density in aqueous solutions. Starting with a standard solution of 10 g of salt dissolved in 100 ml of water, resulting in a molarity of approximately 1.71 M, five distinct samples are meticulously prepared. These samples cover a range of NaCl concentrations, with different ratios of salt solution and drinking water, including pure water, 10 ml of salt solution with 90 ml of water, 20 ml of salt solution with 80 ml of water, 30 ml of salt solution with 70 ml of water, and 40 ml of salt solution with 60 ml of water. Each sample undergoes analysis using the developed microwave sensor to determine its transmission coefficient. The magnitude of the transmission coefficient is closely tied to the density of the salt solution based on molarity. Through a detailed regression analysis, a strong quantitative relationship between the transmission coefficient and salt solution density is revealed. This correlation can be accurately represented by a third-order polynomial equation. This research is significant as it advances microwave sensor technology, allowing for accurate and efficient measurement of NaCl density in water.**

***Keywords— Aqueous solution, Microwave sensor, Resonance frequency, Split-ring resonator, Transmission coefficient***

## I. INTRODUCTION

The accurate measurement of sodium chloride (NaCl) density in water is crucial in a variety of fields, such as environmental impact assessment, agricultural soil salinization prevention, industrial process quality control, medical treatments, and food and beverage preservation [1, 2]. However, conventional methods for determining NaCl density in water solutions have limitations, including the need for sample preparation and large sample volumes, which can affect the precision and accuracy of the measurements [3 – 5]. As a result, there is a growing demand for innovative and efficient measurement techniques.

One such technique is the utilization of planar microwave sensors, which have seen significant advancements in recent years, particularly in material characterization (solid/liquid) due to their high sensitivity to density changes [6]. Microwave sensors have been successfully employed to identify and categorize water solutions containing NaCl, KCl, $CaCl_2$, $MgCl_2$, and $Na_2CO_3$ [7]. Additionally, a study has demonstrated the use of a planar antenna-based sensor immersed in sediments for monitoring water content in such materials [8]. Another study has showcased the visualization of microwave near-field distribution in NaCl and glucose solutions using a thermo-elastic optical indicator microscope [9].

Recent studies have provided new insights into the disadvantages of current microwave sensors used to measure NaCl in aqueous solutions. For example, Bakam Nguenouho *et al.* [10] proposed an innovative microwave-based sensor that can accurately determine the concentrations of both NaCl and sucrose in ternary solutions. This sensor addresses the need for precise and real-time data in various applications. The design of the sensor in [10] consists of two facing split-ring resonators (SRRs). Similarly, Chudpooti *et al.* [11] introduced an in-situ self-aligned fluidic-integrated microwave sensor for characterizing NaCl contents in solutions. They highlighted the advantages of microwave sensors over conventional liquid and fluidic sensors. However, this study also emphasized the limitations in terms of the sensor's size and the complexities involved in the measurement process. Additionally, Babajanyan *et al.* [12] discussed the use of a near-field microwave microprobe for NaCl sensing, which had limitations in terms of the sensor's size and the requirement for a high Q dielectric resonator. Similarly, the microwave sensor proposed by Harnsoongnoen *et al.* [13] demonstrates its usefulness in detecting and classifying water containing NaCl, KCl, $CaCl_2$, $MgCl_2$, and $Na_2CO_3$. Although the planar microwave sensor is suitable for various applications, its relatively large size and laborious setup during the measuring process need to be considered. These recent findings highlight the importance of addressing the limitations of current microwave sensors for measuring NaCl density.

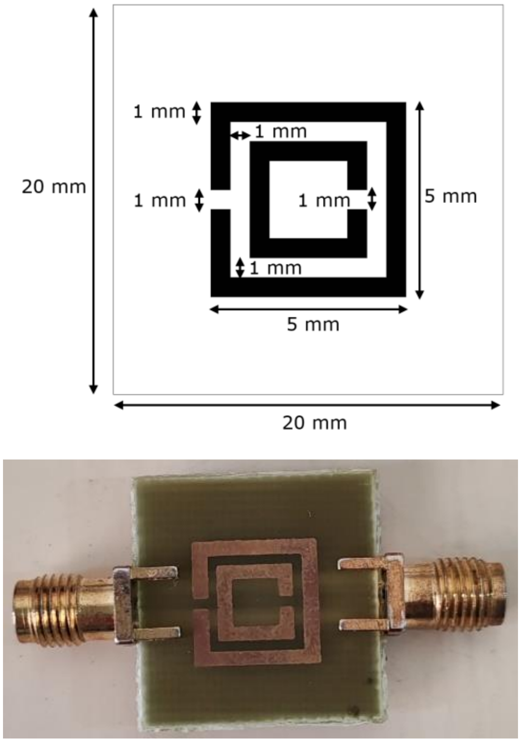
In response to these limitations, the aim of the research presented in this paper is to build a simple, small, and portable yet accurate microwave sensor for measuring the density (in terms of molarity) of NaCl in aqueous solutions. The development of such a sensor is expected to contribute to the advancement of microwave sensor technology, enabling the accurate and efficient measurement of NaCl density in water, and addressing the current limitations of existing sensors.

## II. DESIGN OF THE MICROWAVE SENSOR

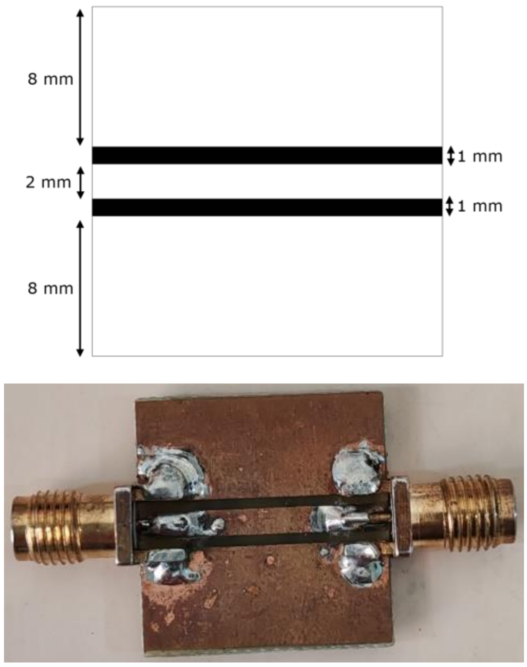
The key element in developing the microwave sensor for NaCl density measurement is the implementation of a resonator. To create a resonator that produces a distinct dip in the transmission coefficient, we have positioned a square split-ring resonator (SRR) atop an FR4 substrate, which has a thickness of 1.6 mm, dielectric constant of 4.4 and loss tangent of 0.022. This was complemented by a coplanar waveguide (CPW) transmission line at the base of the substrate. Both the SRR and CPW are etched on a 0.035 mm thick copper layer. The choice of the SRR is based on its ability to establish a resonant structure that is highly responsive to electromagnetic waves at specific frequencies. This makes it an ideal sensing element for detecting changes in dielectric properties influenced by NaCl density.

The sensor was first simulated using Ansys High Frequency Structure Simulator (HFSS) so that its performance characteristics could be empirically fine-tuned. The final optimized structure was then fabricated for validation. Figure 1 illustrates the top and bottom views of the proposed sensor. As can be seen from the figure, the footprint of the sensor merely constitutes an area of 20 mm × 20 mm, which is considerably compact.

Upon introducing a sample onto the SRR, variations in dielectric properties induce changes in the resonance frequency and/or amplitude of the transmission dip [14 – 17]. For validation purposes, 10 g of NaCl was dissolved in 100 ml of water, yielding a concentration of approximately 1.7 M. Five distinct Samples Under Test (SUTs) were then prepared based on the NaCl solution. These SUTs encompassed 100 ml of pure drinking water (without NaCl) and four sets of 100 ml aqueous solutions with different NaCl-to-water ratios, yielding concentrations of 0 M, 0.17 M, 0.34 M, 0.51 M, and 0.68 M of NaCl. These SUTs, housed in test tubes, were placed on the sensor, as depicted in Fig. 2. Subsequent changes in the transmission coefficient of the resonance band were meticulously observed and recorded through a vector network analyzer (VNA).




(a)




(b)

Fig. 1. The (a) top and (b) bottom views of the proposed microwave sensor's topologies and fabricated structure.

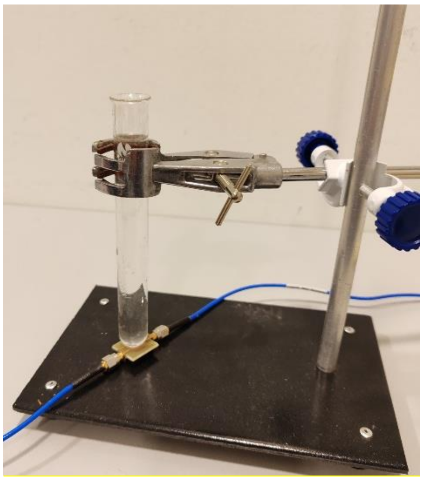


Fig. 2. Experimental setup to measure the concentration of NaCl solution.

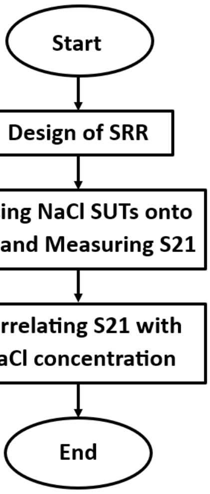



Fig. 3. Flowchart of the design methodology.

To facilitate the prediction of NaCl concentration, the fluctuation in the transmission coefficient at resonance frequency is mathematically linked to the molarity of NaCl in the solution. This correlation enables estimation of NaCl concentration through polynomial equations. Figure 3 illustrates a synopsis of the design process.

## III. RESULTS AND DISCUSSION

Figure 4 depicts the variations in the transmission dip concerning different concentrations of NaCl solution. In the absence of NaCl (i.e., in the SUT comprising 100 ml of pure drinking water), the sensor's transmission coefficients register values of -5.46 dB and -5.50 dB at resonance frequencies 3.85 GHz and 4.10 GHz, respectively. As the concentration of NaCl increases, however, a discernible decrement in the transmission dip becomes evident, as illustrated in the figure. The findings suggest that the microwave device exhibits enhanced impedance matching at higher NaCl concentrations, consequently facilitating an improvement in the propagation of electromagnetic signal to the output port of the sensor.

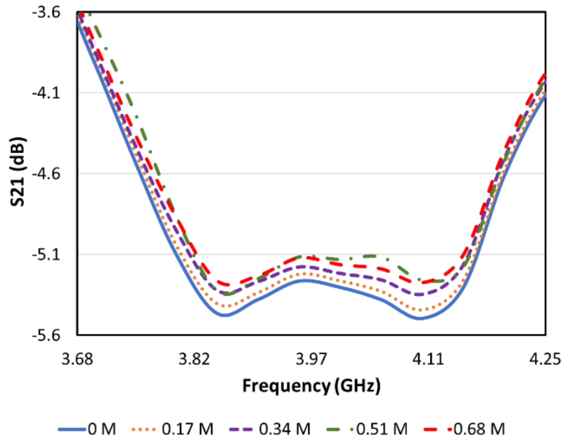



Fig. 4. The transmission coefficients of the microwave sensor when measuring Samples Under Test (SUTs) with 0 M (solid line), 0.17 M (dotted line), 0.34 M (short-dashed line), 0.51 M (dashed-dotted line), and 0.68 M (long-dashed line) of NaCl solutions.

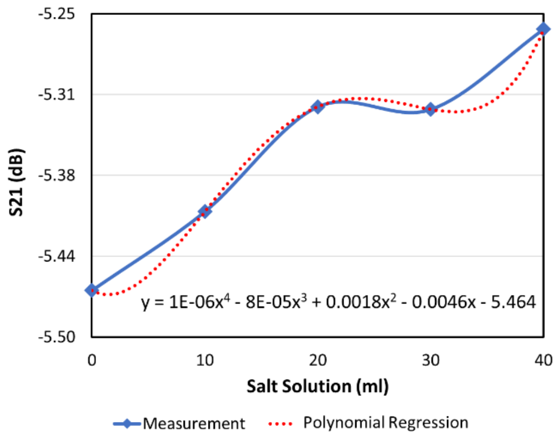



Fig. 5. Relationship between the transmission coefficient and NaCl concentration at $f_r$ = 3.85 GHz. The solid line represents the empirical relationship between them, while the dotted line illustrates the mathematical correlation computed using Eq. (1).

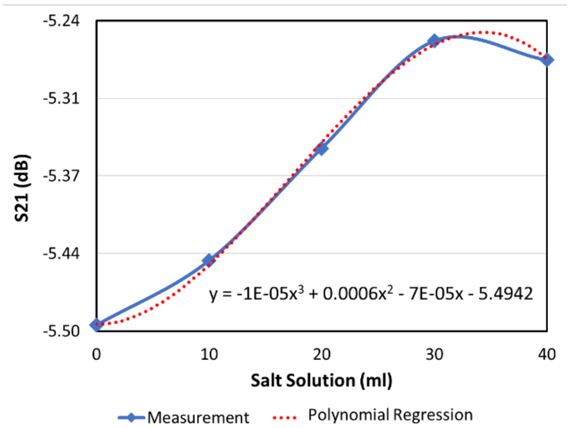



Fig. 6. Relationship between the transmission coefficient and NaCl concentration at $f_r$ = 4.10 GHz. The solid line represents the empirical relationship between them, while the dotted line illustrates the mathematical correlation computed using Eq. (2).

In order to establish a correlation between the concentrations of NaCl in the aqueous solution and the corresponding variations in transmission dips, the transmission coefficients ($t$) at resonance frequencies are graphically represented against the molarity of NaCl ($s$), as illustrated in Figs. 5 and 6. Upon closer examination, it becomes evident that the observed curves can be effectively modelled using a fourth- and a third-order polynomial regression. The mathematical expressions representing the relationship between $t$ and $s$ at $f_r$ = 3.85 GHz and 4.1 GHz are respectively formulated as Eq. (1) and Eq. (2) below

$$t = 12.183s^4 - 15.933s^3 + 6.0218s^2 - 0.268s - 5.464, \quad (1)$$

$$t = -2.4332s^3 + 2.1447s^2 - 0.004s - 5.4942. \quad (2)$$

Table I. The actual and predicted concentrations of NaCl solution.

| Actual Concentration (M) | Predicted Concentration (M) | Error (%) |
|---|---|---|
| 0.00 | 0.00 | 0 |
| 0.17 | 0.18 | 5.88 |
| 0.34 | 0.33 | 2.94 |
| 0.51 | 0.53 | 3.92 |
| 0.68 | 0.69 | 1.47 |

Upon scrutiny of Figs. 5 and 6, it becomes apparent that the fluctuations in transmission coefficients at resonance frequency $f_r$ = 4.1 GHz align more closely with the polynomial regression model. Additionally, owing to the inherent ease of solving cubic equations, Eq. (2) is deemed preferable for implementation over Eq. (1). By substituting the value of $t$, a root-searching algorithm can be employed to ascertain the concentration of NaCl ($s$). In this context, the SymPy library in Python has been employed to facilitate this computational process. A comprehensive comparison between the actual concentration of NaCl and the predicted values is summarized in Table I. The tabulated results distinctly indicate that the prediction errors are consistently below 6%, with the minimum registering at 0%. This remarkable accuracy in prediction error underscores the sensor's precision in measuring NaCl concentration. In comparison with contemporary microwave sensors found in the literature, it can be seen that the accuracy of the proposed sensor is comparable to that reported in [11] (below 4%) and superior to that in [10] (above 10%).

## IV. CONCLUSION

The study presented in this research aims to fulfil the critical requirement for a fresh and inventive method to measure the density of sodium chloride (NaCl) in water-based solutions. Conventional techniques have their constraints, which highlights the necessity for the creation of more effective measurement methods. The primary focus of this research is on the development and verification of a small microwave sensor that employs a square split-ring resonator (SRR) and coplanar waveguide (CPW). The decision to utilize an SRR is supported by its responsiveness to electromagnetic waves, rendering it suitable for detecting alterations in NaCl density.

For the simulation and production of the sensor, Ansys High-Frequency Structure Simulator (HFSS) was employed. A sensor with a compact size of 20 mm × 20 mm was developed. Validation trials were carried out by introducing NaCl solutions with different concentrations onto the sensor. These trials illustrated the sensor's ability to identify changes in transmission coefficients at resonance frequencies. The research also suggests mathematical models to elucidate the observed variations, with Eq. (2) being favoured due to its cubic nature and simplicity in resolution.

Polynomial regression models effectively capture the relationship between NaCl concentrations and transmission coefficients. By utilizing a root-searching algorithm based on Eq. (2), it becomes possible to accurately determine the NaCl concentration. The accuracy of this method is demonstrated through a comprehensive comparison with actual concentrations in Table I, revealing consistently low prediction errors below 6%, with the minimum error recorded at 0%. These findings emphasize the precision of the sensor in measuring NaCl concentration.

To summarize, the proposed microwave sensor exhibits promising accuracy and provides a straightforward, compact, and portable solution to address the limitations of existing techniques for measuring NaCl density. This research contributes to the advancement of microwave sensor technology and holds potential for applications in various fields that require precise measurement of NaCl density.

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