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Microwave Sensing of Sugar Solution Concentration Using a 2.4 GHz Microstrip Antenna

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ABSTRACT

Microstrip antennas are widely used in sensing applications according to compact, low-cost, and easy to fabricate. This study presents the design and evaluation of a 2.4 GHz circular patch microstrip antenna integrated with a split-ring resonator (SRR) for sensing sugar-solution concentration through dielectric property induced perturbations. The antenna employs an inset feed configuration and is implemented on an FR4 substrate. The design and parametric analysis are carried out in simulation by placing sugar solutions with mole fractions from 0 to 0.04 in the sensing region. In result, we observe changes in resonant frequency, minimum return loss, and quality factor (Q). The simulations indicate monotonic trends with concentration, with the minimum return loss becoming less negative as concentration increases, accompanied by reductions in resonant frequency and Q. Experimental measurements of the fabricated prototype, however, show weaker and less consistent correlations across the same parameters, highlighting the sensitivity of the response to practical factors such as sample positioning, fabrication tolerances, and measurement repeatability.

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1. INTRODUCTION

Sugar is a vital component in human life, serving as a primary energy source that is easily absorbed by the body. Its demand continues to increase to meet the needs of the food and pharmaceutical industries, as well as its use as a raw material in bioconversion processes [1-3]. Sugar is widely present in various sweet foods and beverages. In Indonesia, the consumption of high-sugar foods and drinks has grown increasingly popular among the public. However, excessive sugar intake can adversely affect health, with one of the most notable consequences being a higher risk of obesity [4-5]. Therefore, to avoid excessive sugar consumption, it is essential to monitor and quantify the amount of sugar being consumed.

Like most substances, sugar exhibits specific electrical properties influenced by internal factors such as moisture content, chemical composition, acidity level, and other intrinsic characteristics. One important electrical property is the dielectric constant, which indicates a material's ability to store electric charge. The dielectric constant varies according to the concentration of the substance within a solution [6-7].

The relationship between solution concentration and dielectric constant has long been an important topic of interest across disciplines, including physical chemistry and sensing technology. This relationship is significant because the dielectric constant of a solution not only reflects its electrical properties but can also provide valuable information regarding changes in its internal structure and composition. In practical applications, understanding dielectric behavior is useful for accurately measuring solution concentration, monitoring crystallization processes in industrial settings, and developing electrochemical sensors that detect chemical environment changes [8-10].

With rapid technological advancements, particularly in wireless communication, various devices have been developed to address challenges in sugar concentration detection. One of the most widely used wireless technologies is the microstrip antenna. Its selection is motivated by advantages such as ease of fabrication, low production cost, mechanical robustness, fast response, and high sensitivity [11-13]. A microstrip antenna can function as a microwave sensor by detecting changes in the dielectric properties of materials located within its near-field region [6]. Although simple, this method holds great potential for development as a non-contact, real-time sugar concentration sensor, particularly beneficial for the beverage industry in maintaining product quality efficiently.

Several previous studies have explored microstrip antennas as sensors for detecting salt and sugar concentrations in water. One such study [14-16], utilized a crescent-shaped radiating element operating from 2.50 GHz to 18 GHz. The antenna served as a sensor to detect salt and sugar content based on the dielectric constants of the solutions. The results indicated that solution concentration is inversely proportional to dielectric constant, where increases in salt or sugar content led to decreases in dielectric constant. Another relevant study [18-20], used salt and sugar samples tested by immersing the antenna directly into solution containers. The findings revealed that higher salt or sugar concentrations increased reflection coefficients, while the dielectric constant decreased.

This work proposes the design of a circular-patch microstrip antenna integrated with a Split Ring Resonator (SRR) operating at the 2.4-GHz WiFi band for sensing variations in sugar-solution concentration. The proposed antenna leverages the sensitivity of resonant structures to dielectric changes, enabling detection based on shifts in resonant characteristics. The detailed design, simulation, and performance evaluation of the antenna as a microwave-based sugar concentration sensor are presented in this paper.

2. RESEARCH METHOD

The first stage of the design process involves determining the operating frequency of the antenna, which is set at 2.4 GHz, along with the desired antenna characteristics, namely VSWR and return loss. The antenna dimensions—including the patch, ground plane, feed line, and substrate—are then calculated using standard design equations, followed by the integration of an SRR structure on the patch. After obtaining the antenna dimensions, a tube is added as the container for sugar-solution testing. The tube is cylindrical with a diameter of 15 mm and a height of 40 mm. The complete design is subsequently simulated using CST Studio Suite. If the simulation results do not meet the expected antenna parameters and target performance, an optimization process is carried out.

Once the antenna optimization is completed, simulations are performed to obtain the return loss and VSWR values prior to the introduction of the sugar solution. Sugar solutions with mole fractions ranging from 0 to 0.040 are then tested using the tube, based on their dielectric constants. The results of these evaluations are analyzed to draw conclusions. The flowchart of the research procedure is illustrated in Figure 1.

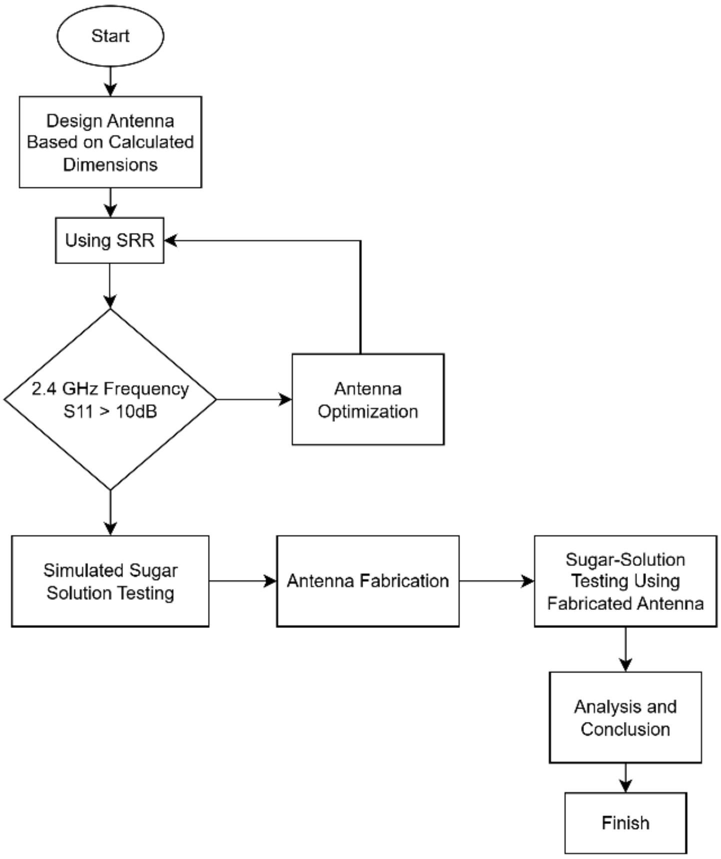


Figure 1. Flowchart of the antenna design and testing process

2.1. Antenna Calculation

The antenna substrate is composed of a dielectric material whose properties have a significant impact on the antenna performance. Different substrate types exhibit varying dielectric constant (ε_r) and dielectric loss tangent (tan δ). In this work, an FR4 (Epoxy) substrate is employed, and its material characteristics are summarized in Table 1.

Table 1. FR4 (Epoxy) substrate characteristics

Spesification	**Value**
Dielectric Constant (ε_r)	4.4
Substrate thickness	1.6 mm
Dielectric loss tangent ($tan\ \boldsymbol{\delta}$)	0.02

The patch used in this design has a circular shape; therefore, the first step is to determine the patch radius. Prior to calculating the radius, the logarithmic function of the patch (F) must be obtained. The logarithmic function for the circular patch represents the resonant frequency equation and the dielectric constant of the antenna substrate. To obtain the radius of the antenna patch (a), the calculation is performed using the logarithmic function, the substrate thickness, and the substrate dielectric constant, as shown in the equation below.

$$F = \frac{8{,}791 \times 10^9}{2.4 \times 10^9 \sqrt{4.4}} = 1.746$$

$$a = \frac{1.746}{\left\{1 + \frac{2 \times 0.16\ cm}{3.14 \times 4.4 \times 1.746}\left[\ln\left(\frac{3.14 \times 1.746}{2 \times 0.16}\right) + 1.7726\right]\right\}^{1/2}}$$

$$a = 1.69\ cm = 16.9\ mm \approx 17\ mm$$

2.2. Split Ring Resonator (SRR)

A Split Ring Resonator (SRR) is an artificial structure used to implement planar technology and is commonly applied in compact microwave components. An SRR is typically made of a metallic material and consists of two closed conductive rings with splits positioned on opposite sides. The spacing between the two rings introduces a high capacitance value, which leads to a reduction in the resonant frequency. SRRs are widely used to enhance the performance of information and communication technology devices—particularly filters and antennas—without altering their primary features or increasing their physical dimensions. The type, pattern, arrangement, and gap spacing of the SRR significantly influence the resulting electromagnetic behavior [15]. SRR structure can shown in Figure 1.

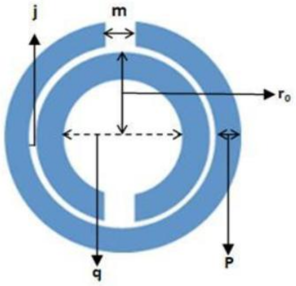


Figure 2. SRR structure

The proposed sensing antenna incorporates a Split Ring Resonator (SRR) structure that is embedded within the radiating patch to enhance the electric-field concentration in the designated sensing region. The SRR functions as a subwavelength resonant inclusion capable of supporting strong localized electric fields due to its capacitive gap and circulating surface currents. This local field enhancement mechanism is critical for improving the interaction between the electromagnetic wave and the analyte under test, thereby increasing the overall sensitivity of the sensor to small variations in the dielectric properties of sugar–water solutions.

The design process began with a conventional rectangular microstrip patch operating at the target resonant frequency. Subsequently, a single-stage and later a multi-stage SRR topology were evaluated to determine the configuration providing the highest perturbation response. Key geometrical parameters—including the outer ring radius, ring width, inter-ring spacing, and the gap size—were systematically optimized using full-wave electromagnetic simulations. A parametric sweep was performed to study the impact of each parameter on the resonance shift, electric-field distribution, and quality factor (Q-factor). The SRR was strategically positioned at the location of maximum electric-field density on the patch to maximize its coupling to the sensing medium.

To account for the presence of the liquid sample, a fluidic channel (or dielectric layer) was modeled above the SRR region, enabling accurate prediction of the field–matter interaction. Boundary conditions, substrate material properties, and meshing strategies were carefully selected to ensure numerical stability and convergence. The final antenna layout, including the SRR configuration, feedline geometry, and sensing chamber placement, is illustrated in Figure 3.

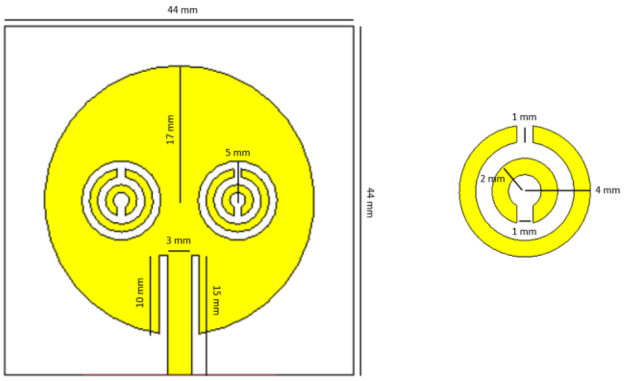


Figure 3. Antenna design

2.3. Sugar Solution Sensing

A solution is a homogeneous mixture consisting of two or more substances with variable composition. The substance present in a smaller amount is referred to as the solute, while the substance present in a larger amount is known as the solvent. The properties of a solution are strongly influenced by its composition, which is expressed through its concentration. This concentration represents the ratio of the amount of solute to the amount of solvent [18].

The concentration of a solution represents the ratio between the amount of solute and the amount of solvent. The solubility of a substance can vary widely, ranging from very low to very high. If the amount of solute exceeds its saturation point, the excess solute will precipitate at the bottom of the solution. Under certain conditions, a solution may contain more solute than the amount normally present at saturation. The concentration of a substance can be expressed in various ways, one of which is the mole fraction, denoted by X. The formula for the mole fraction is shown in the following equation [19].

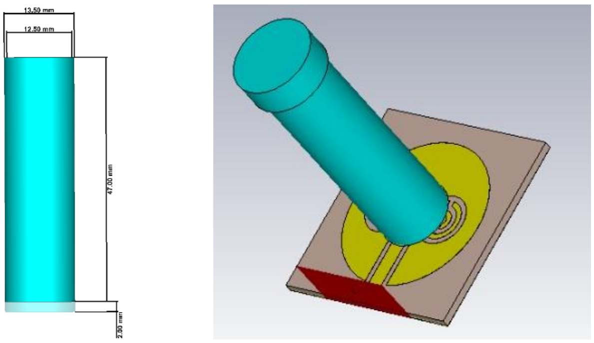
$$Mole\ Fraction = X_A = \frac{Number\ of\ moles\ of\ A}{Total\ number\ of\ moles\ of\ all\ components}$$

Sugar is a form of carbohydrate that serves as a primary energy source for the body and provides sweetness to food and beverages. One type of sugar is sugar, a simple carbohydrate commonly referred to as a simple sugar. Sugar is widely used as an additional sweetener [20]. Sugar can be found in several forms, including anhydrous sugar and monohydrate sugar. The primary difference between these forms lies in the presence of water molecules within their structures.

Anhydrous sugar is the pure form of sugar without any crystalline water molecules, meaning each sugar molecule ($C_6H_{12}O_6$) stands alone. This form is often used in the pharmaceutical and food industries due to its high purity and greater stability against moisture [21]. In contrast, monohydrate sugar contains one water molecule bound within its crystalline structure for each sugar molecule. Its chemical formula is $C_6H_{12}O_6 \cdot H_2O$. This form is more commonly available and frequently used in products requiring rapid solubility or as a sweetener in beverages and processed foods. The presence of the water molecule results in slight differences in molecular weight and certain physical properties compared to anhydrous sugar [22]. When sugar is dissolved in water, it forms a sugar solution. This solution is classified as a non-electrolyte, meaning it does not conduct electricity because it does not produce free-moving ions in the solution [5].

The performance of the proposed antenna as a dielectric sensor was experimentally evaluated using a cylindrical sample holder positioned precisely above the sensing region of the antenna, as illustrated in Figure 4. The cylindrical container, fabricated from a low-loss dielectric material to minimize additional parasitic loading, was employed to confine and stabilize the liquid under test during measurement. Its geometry ensures uniform sample thickness above the SRR-enhanced sensing area, thereby improving measurement repeatability and reducing uncertainty caused by sample displacement or surface perturbations.

During testing, the cylindrical vessel was aligned with the antenna's electric-field hotspot to maximize electromagnetic coupling between the resonant structure and the sugar–water solutions. The container dimensions—specifically, its inner diameter, wall thickness, and height—were selected to avoid unintended resonances or mode coupling that could distort the antenna's response. All samples were introduced into the holder in controlled volumes to maintain a constant sensing depth across measurements.



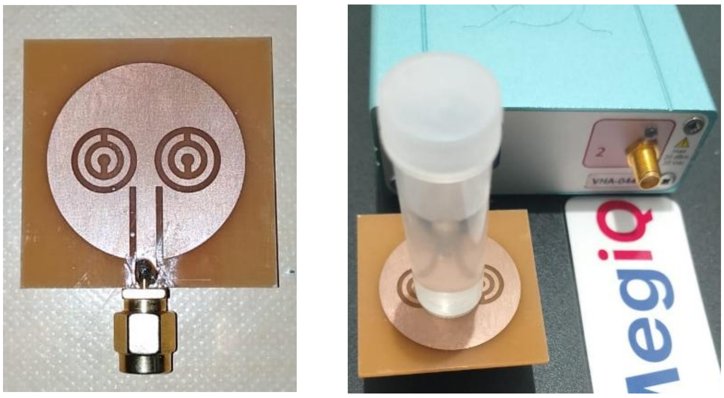
(a) (b)

Figure 4. (a) Tube dimension, (b) Tube position

3. RESULTS AND DISCUSSION

The experimental evaluation was conducted to investigate the influence of sugar-solution concentration on the antenna's sensing characteristics, including return loss, VSWR, resonant frequency, and quality factor (Q-factor). A fixed sample volume of 4 mL was used for all measurements to maintain consistent sensing depth and minimize geometric variations within the sensing region.

Sugar–water solutions were prepared with molar fractions ranging from 0 to 0.04, with an incremental step of 0.005 between successive concentrations. Each solution was introduced into the cylindrical sample holder and positioned above the antenna as described previously. For every concentration level, the antenna response was recorded using a calibrated Vector Network Analyzer (VNA), ensuring that any observed variations in the measured parameters were solely attributable to changes in the dielectric properties of the solution



(a) (b)

Figure 5. (a) Antenna fabrication, (b) Measurement procedure using a Vector Network Analyzer

3.1. Simulation Result

The frequency variation after measurement is presented in Figure 6. As shown, the antenna's resonant frequency exhibits a slight decrease with increasing sugar molar fraction before stabilizing. This behavior does not align with the general theoretical expectation, in which a reduction in dielectric constant should cause the resonant frequency to increase. One possible explanation for this phenomenon is the use of the SRR structure in the antenna design, which results in a more complex electric-field response. A decrease in dielectric constant may alter the electric-field distribution around the sensing region, leading to a nonlinear or even counterintuitive resonant behavior compared to conventional theory.

Therefore, the frequency response is influenced not only by the dielectric constant itself but also by how the solution affects the electromagnetic field distribution around the patch and the SRR elements. Furthermore, Figure 6 shows that beyond a molar fraction of 0.025, the resonant frequency tends to remain constant, indicating a saturation point in the solution's influence on the antenna resonance. This also suggests a reduction in system sensitivity to further changes in the dielectric constant.

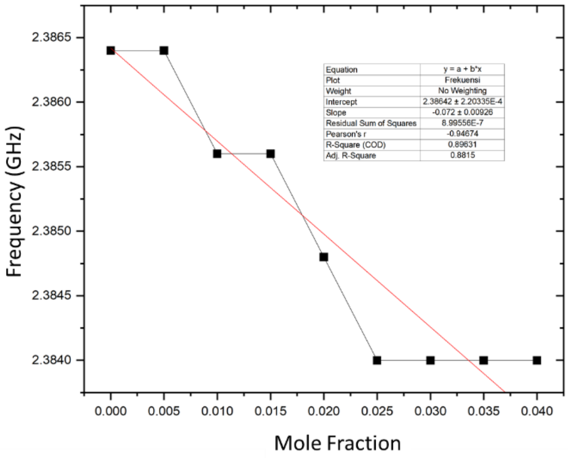


Figure 6. Simulated frequency resonant response

In the simulation-based evaluation, the antenna exhibited noticeable variations in the return loss characteristics after the introduction of sugar solutions. At a mole fraction of 0 (pure water), the simulated return loss was measured at –14.711 dB. As the mole fraction of sugar increased, the return loss showed a consistent upward trend, indicating a progressive degradation in impedance matching due to changes in the dielectric properties of the sensing medium.

Figure 7 presents the simulated return loss obtained after varying the sugar-solution concentration. A clear linear relationship is observed between the mole fraction of sugar and the return loss magnitude. As the mole fraction increases, the return loss performance degrades, with its value shifting closer to 0 dB, indicating higher power reflection and reduced impedance-matching efficiency. This degradation is accompanied by a resonance-frequency shift toward lower frequencies, which is attributed to the decrease in the effective dielectric constant of the solution. The resulting change in dielectric characteristics drives the system away from its optimal matching condition, thereby reducing the overall return-loss performance.

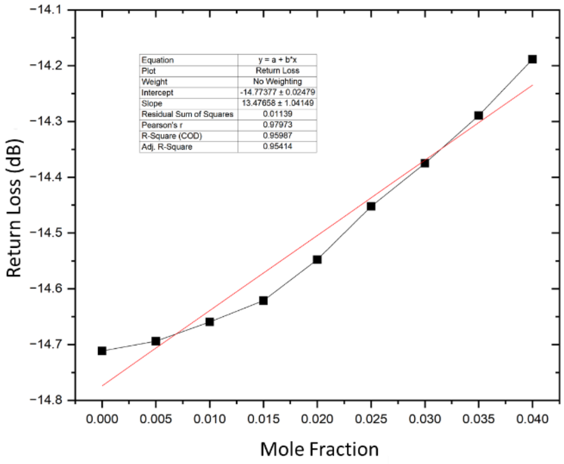


Figure 7. Simulated return loss response

The relationship between the mole fraction of the sugar solution and the return loss can be analyzed using a simple linear regression model. The linear regression equation describes the effect of the sugar-solution mole fraction (x) on the return loss (y). The model also includes the coefficient of determination (R^2), which indicates how much of the variation in the return loss (y) can be explained by changes in the mole fraction (x). In other words, R^2 represents the percentage of variability in y that is attributable to x, while the remaining portion is influenced by other factors. Because the predicted y values are not perfectly accurate, the Root Mean Square Error (RMSE) of the regression model is also computed to evaluate the model's prediction error. In addition, the strength of the linear relationship between x and y is quantified using the correlation coefficient (R). From the return-loss graph, the correlation coefficient is calculated to be 0.97973, and the coefficient of determination is 0.95987. This indicates that 95.99% of the variation in return loss is explained by the mole fraction of the sugar solution, with the remaining portion caused by other factors. The RMSE obtained from the regression equation is 0.03557491.

The simulated antenna test shows a change in the Q factor compared to the value obtained prior to the addition of the sugar solution. The Q factor at a mole fraction of 0 is 50.77447, whereas after increasing the mole fraction to 0.010, the Q factor decreases slightly to 50.75745. The frequency response after testing is presented in Figure 8. It can be observed that the Q-factor decreases as the sugar solution concentration increases. This trend indicates that higher molar fraction or dielectric constant values lead to a lower antenna Q-factor. Consequently, the antenna exhibits reduced frequency selectivity and a broader bandwidth. The reduction in Q-factor ultimately degrades the sensor's frequency-shift resolution.

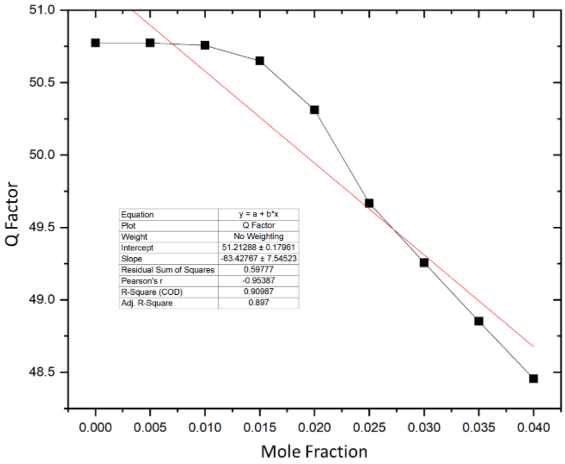


Figure 8. Simulated Q-factor response

The relationship between the molar fraction of the sugar solution and the Q-factor can be analyzed using a simple linear regression model. In this model, the coefficient of determination (R^2) quantifies how much of the variation in (y) is explained by changes in (x). In other words, the variation in the Q-factor is explained by the molar fraction of the sugar solution, while the remaining percentage is attributed to other uncontrolled factors. This indicates that the predicted values are not entirely accurate, and therefore the Root Mean Square Error (RMSE) must also be evaluated to assess the model's reliability. Additionally, the strength of the linear relationship is measured using the correlation coefficient. From the Q-factor regression plot, the correlation coefficient is obtained as −0.95387 and the coefficient of determination as 0.90987. These results indicate that the molar fraction of the sugar solution contributes 90.99% to the variation in the Q-factor, while the remaining variation is influenced by other factors.

3.2. Measurement of the Fabricated Antenna Using the Solution

The frequency variation after measurement is presented in Figure 9. It can be observed that changes in the sugar molar fraction do not exhibit a linear relationship with the resonant frequency. The measured frequency values fluctuate irregularly, indicating that the addition of sugar does not consistently affect the antenna's resonant behavior. However, despite these fluctuations, a general downward trend in frequency can still be identified at certain molar fraction intervals.

Theoretically, increasing sugar concentration should lower the dielectric constant of the solution and consequently increase the resonant frequency. One possible cause of the deviation from this expected behavior is the non-uniformity of the sugar solution, resulting in micro-scale concentration variations that affect the local dielectric properties around the patch and SRR. Additional factors, such as interference from the connectors, non-ideal substrate characteristics, and fabrication imperfections on the patch and SRR gaps, may also introduce unexpected perturbations in the resonant pattern. Since microstrip antennas are highly sensitive to their surrounding environment, particularly in regions of strong electric fields such as the patch and SRR gaps, even small variations can significantly disrupt the resonance characteristics.

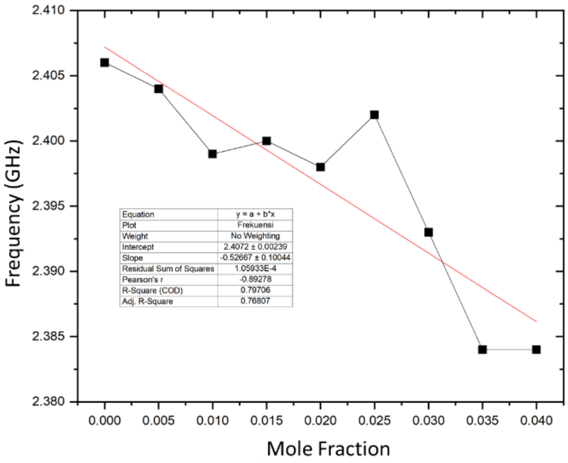


Figure 9. Measured frequency resonant of the fabricated antenna

The fabricated antenna was printed and soldered at the feed line, where an SMA connector was attached to interface the antenna with the measurement equipment. Sugar solutions with molar fractions ranging from 0 to 0.040, at an interval of 0.005, were used for the measurements. During testing, each sugar solution was placed in a tube with a volume of 4 mL. A vector network analyzer (VNA) was employed to characterize the antenna, and all measurements were conducted in the Telecommunication Laboratory. The measurement results of the fabricated antenna were then compared with the simulation results to identify and analyze the sources of discrepancy between the two.

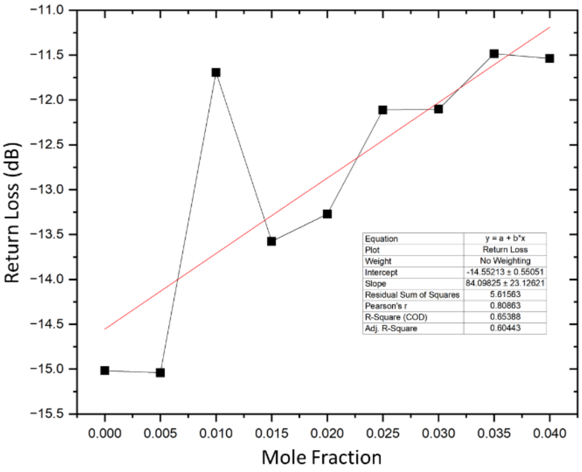


Figure 10. Measured return loss of the fabricated antenna

From the return loss plot in Figure 10, the correlation coefficient is obtained as 0.80863, while the coefficient of determination (R^2) is 0.65388. This indicates that the molar fraction of the sugar solution accounts for 65.39% of the variation in the return loss, with the remaining variation influenced by other factors. The RMSE calculated from the corresponding linear regression model is 0.7899104.

The Q-factor variation after measurement is presented in Figure 11. The relationship between the sugar molar fraction and the Q-factor is non-linear and does not exhibit a consistent trend. The Q-factor values fluctuate as the molar fraction increases, with an average value of 49.5. From the Q-factor plot,

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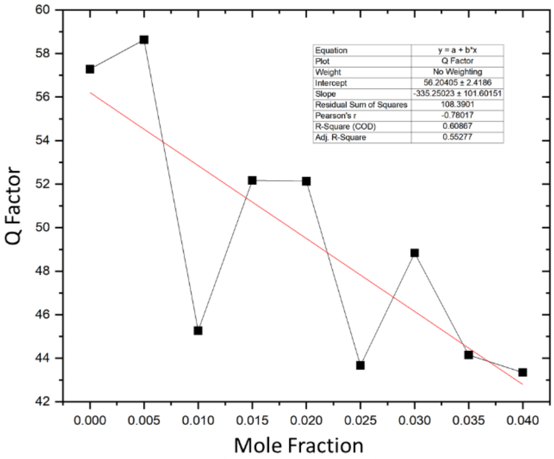
the correlation coefficient is obtained as –0.78017, while the coefficient of determination (R^2) is 0.60867. This indicates that the molar fraction of the sugar solution accounts for 60.87% of the variation in the Q-factor, with the remaining variation influenced by other factors. The RMSE computed from the corresponding linear regression model is 3.47035054.



Equation	y = a + b*x
Plot	Q Factor
Weight	No Weighting
Intercept	56.20405 ± 2.4186
Slope	-335.25023 ± 101.60151
Residual Sum of Squares	108.3901
Pearson's r	-0.78017
R-Square (COD)	0.60867
Adj. R-Square	0.55277

Figure 11. Measured Q-factor of the fabricated antenna

3.3. Comparison of Simulated and Measured Antenna Performance

Based on Figure 12, a clear difference in the overall trend is observed between the simulated and measured results. The simulated return loss demonstrates a consistent increase with higher molar fractions of the sugar solution, whereas the measured return loss exhibits a fluctuating and irregular pattern. These discrepancies can be attributed to several factors, including suboptimal soldering at the feed line, dimensional tolerances between the simulated and fabricated prototypes, variations in substrate material properties, and the inherent measurement uncertainty of the instrumentation used.

In addition, environmental factors—such as temperature, humidity, and the presence of surrounding objects may influence the measured response, as fabricated antennas are significantly more sensitive to external perturbations compared to their simulated counterparts. The simulation environment benefits from idealized conditions with perfect material models and boundary settings, thereby minimizing noise and parasitic effects. Conversely, the fabricated antenna is influenced by manufacturing imperfections, slight misalignments, and non-ideal feeding conditions, all of which contribute to the observed deviations.

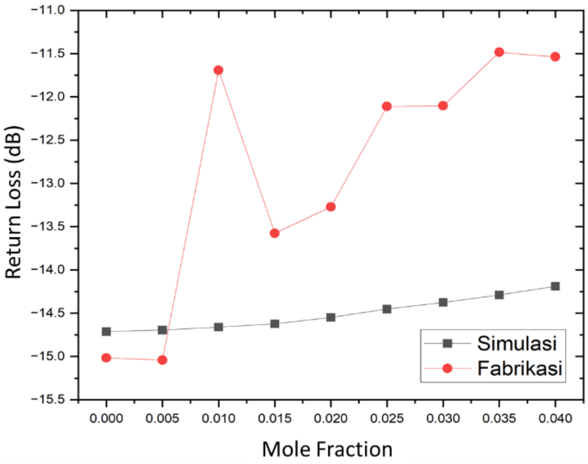


Figure 12. Comparison of the simulated and measured return loss

Based on the plot in Figure 13, a clear difference in trend can be observed between the simulated and measured results. The simulated Q-factor exhibits a decreasing trend as the molar fraction of the sugar solution increases, whereas the measured Q-factor shows a fluctuating and irregular pattern. These discrepancies can be attributed to several factors, including suboptimal soldering, dimensional deviations between the simulated and fabricated antennas, and variations in connector quality. Simulation-based testing benefits from ideal and highly controlled conditions, resulting in minimal errors caused by external influences. In contrast, measurements on the fabricated antenna are affected by numerous external factors, such as environmental noise, imperfect feeding conditions, and material inconsistencies, which contribute to the non-uniform response.

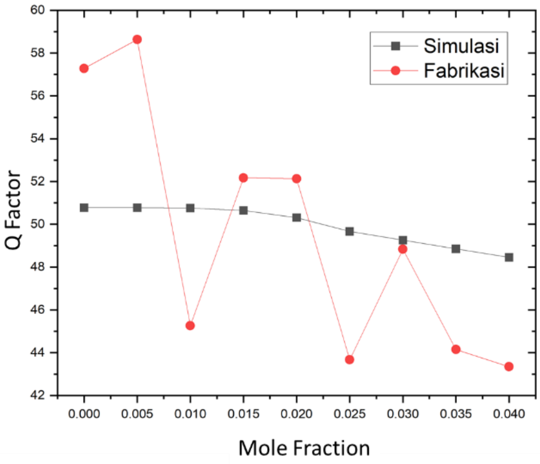


Figure 13. Comparison of the simulated and measured Q-factor

Based on the graph in Figure 14, a clear difference in trend is observed between the simulated and fabricated antenna results. The simulated antenna exhibits a decreasing frequency trend as the molar fraction increases. In contrast, the fabricated antenna shows fluctuating and inconsistent frequency values across the molar fraction variations. These discrepancies can be attributed to several factors, including suboptimal soldering, dimensional deviations between the simulated and fabricated antennas, and variations in the quality of the measurement connectors. Simulation-based testing provides a controlled environment with minimal external interference, thereby reducing the likelihood of measurement errors. Conversely, measurements on the fabricated antenna are influenced by numerous external factors, such as environmental noise, imperfect feeding conditions, and material inconsistencies, all of which contribute to the observed fluctuations in frequency response.

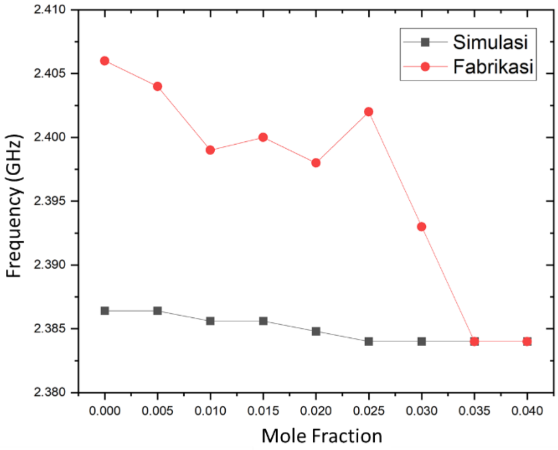


Figure 11. Comparison of the simulated and measured frequency resonant

4. CONCLUSION

This work designed and evaluated a circular-patch microstrip antenna integrated with a split-ring resonator (SRR) for sensing sugar-solution concentration through dielectric perturbation. The simulation results show consistent monotonic changes in resonant frequency, minimum return loss, and quality factor as the sugar concentration increases, indicating that the proposed antenna–SRR structure is sensitive to concentration-dependent dielectric variations under controlled modeling conditions. Measurements on the fabricated prototype exhibit weaker and less consistent trends compared with the simulations. Although the experimental responses generally follow the expected direction of change, the increased scatter suggests that practical non-idealities—such as sample positioning, container influence, fabrication tolerances, connector/solder losses, and measurement repeatability—significantly affect the observed sensing performance. Among the evaluated metrics, the resonant-frequency shift appears to be the most robust experimental indicator, while return loss and quality factor are more susceptible to measurement conditions. Overall, the results support the feasibility of the antenna–SRR approach for dielectric-based sugar-solution sensing and highlight the need for improved experimental control and material characterization to better align simulations with measurements.

Acknowledgments

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