Available *online* at: http://jarpet.ft.unand.ac.id/
**Jurnal Andalas: Rekayasa dan Penerapan Teknologi**
ISSN (Online) 2797-9024

# Simulation Study of 2.4 GHz Rectangular Microstrip Patch Antenna for Sensing Sugar Content Detection

*Queen Hesti Ramadhamy [1], Muhammad Reval [1], Annisa Maulidya [2], Baik Budi [1], Refki Budiman [1]*

[1] *Department of Electrical Engineering, Andalas University, Padang, Indonesia*
[2] *Department of Environmental Engineering, Andalas University, Padang, Indonesia*

ARTICLE INFORMATION

Received: May 20, 2025
Revised: May 21, 2025
Available online: June 01, 2025

KEYWORDS

Antenna, Microstrip, 2.4 GHz, Simulation

CORRESPONDENCE

E-mail: queenhesti@eng.unand.ac.id

**A B S T R A C T**

This study presents a simulation-based analysis of 2.4 GHz rectangular microstrip patch antenna for sensing sugar content in aqueous solutions. The antenna was designed and simulated using software with performance evaluated based on return loss and resonance frequency shifts in response to changes in the dielectric properties of the sugar solution. The primary objective was to assess the sensitivity of the rectangular microstrip antenna to variations in sugar concentration. The result show that the antenna exhibits measurable resonance frequency shifts as the sugar content in the solution increases, indicating the potential of microstrip antennas as effective, non-invasive sensors for liquid concentration monitoring. These findings contribute to the development of microwave-based sensing technologies, offering insights into the application of microstrip patch antennas for sugar detection and other similar application.

## INTRODUCTION

Carbohydrates such as glucose function as essential metabolic substrates, supplying the majority of the body's energy requirements [1][2]. Nonetheless, chronic overconsumption of sugars has been epidemiologically correlated with a heightened incidence of metabolic disorders, including adiposity, type 2 diabetes mellitus, and cardiovascular pathologies [3][4]. In physicochemical terms, aqueous sugar solutions demonstrate distinct dielectric behavior, where the permittivity is modulated by solute concentration [5]. Empirical data indicates that elevated sugar concentrations lead to a reduction in the relative dielectric constant, a phenomenon quantifiable via classical instrumentation like the parallel plate capacitor setup [6]. Despite its accuracy, this technique entails intricate experimental configurations, limiting its applicability in real-time or field-deployable scenarios. Consequently, there is a critical demand for the advancement of compact, rapid, and non-invasive diagnostic methodologies to evaluate sugar concentrations in liquid matrices.

Microstrip patch antennas have gained significant attention as viable platforms for microwave-based chemical and biosensing applications, owing to their planar geometry, straightforward manufacturing process, cost-effectiveness, and pronounced sensitivity to variations in the permittivity of proximate media [7]. These radiating structures operate by monitoring alterations in key electromagnetic parameters, such as return loss, resonant frequency shift, and voltage standing wave ratio (VSWR)—when subjected to diverse dielectric environments within their near-field region [8]. Previous investigations have validated the capability of microstrip antennas to quantify sugar concentration by analyzing perturbations in these metrics through the use of a Vector Network Analyzer (VNA) [9]. A commonly employed technique in this context is the direct contact sensing approach, wherein the antenna is submerged in the analyte, and the backscattered signals are characterized. As the concentration of sugar escalates, the solution exhibits increased microwave absorption, manifesting as elevated reflection coefficients and a downward shift in resonant frequency. Operating at 2.4 GHz offers distinct advantages due to its compatibility with the ISM frequency band, robust propagation characteristics, and heightened responsiveness in liquid dielectric sensing scenarios [10][11].

Although prior investigations have implemented microstrip-based sensors incorporating intricate configurations—such as circular radiators integrated with embedded microfluidic channels—these architectures frequently encounter operational challenges, including maintenance difficulties and non-uniform analyte distribution. This highlights a notable research deficiency, specifically the limited exploration of rectangular microstrip patch antennas deployed in a direct immersion configuration, which offers greater structural simplicity and operational reliability. Accordingly, this work seeks to assess the functional characteristics of a rectangular microstrip patch antenna resonating at 2.4 GHz for the detection of sugar concentrations in aqueous media via electromagnetic simulation. The primary objective is to quantify the antenna's responsiveness to changes in sugar levels by examining shifts in return loss and resonance frequency. The underlying premise is that elevated sugar concentration reduces the effective permittivity of the solution, thereby inducing a detectable variation in the antenna's spectral response. By addressing this underexplored configuration, the study advances microwave dielectric sensing methodologies and introduces an efficient and scalable approach for liquid analyte characterization using a simplified planar antenna structure.

## METHOD

### *Microstrip Antenna*

Microstrip antennas represent compact and low-profile radiating elements [12]. These antennas are structurally composed of a radiating metallic patch on the top layer, a dielectric substrate at the middle, and a conductive ground plane at the bottom. The metallic patch is positioned at a small spacing from the ground plane, typically ranging from $0{,}003\lambda_o$ to $0{,}05\lambda_o$, where $\lambda_o$ denotes the free-space wavelength. The patch is dimensioned and excited such that it produces maximum radiation in the direction normal to its surface, functioning as a broadside radiator. For rectangular configurations, the patch length ($L$) generally falls within the range of $\lambda_o/3$ to $\lambda_o/2$. The separation between the patch and the ground plane is maintained by the dielectric layer, which influences the antenna's impedance and radiation characteristics. A schematic representation of this antenna structure is provided in Figure 1.

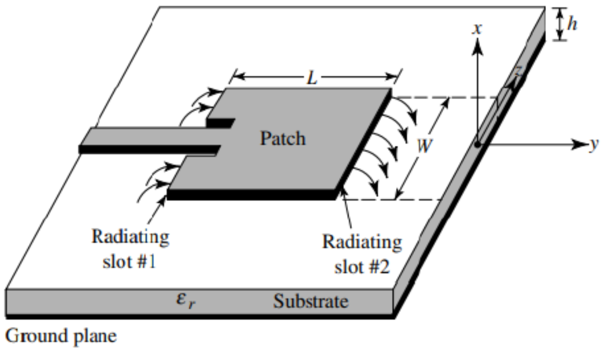


Figure 1. Microstrip Antenna

Dielectric substrates with relative permittivity ($\varepsilon_r$) values ranging from 2.2 to 12 are typically employed in microstrip antenna design. Substrates possessing lower εr and greater thickness are generally favored for antenna applications due to their ability to support higher radiation efficiency, broader operational bandwidth, and enhanced fringing fields that facilitate better coupling into free space—though they tend to result in physically larger structures. In contrast, substrates characterized by higher $\varepsilon r$ and reduced thickness are more appropriate for compact microwave circuit implementations, as they enable tighter electromagnetic field confinement and reduced physical dimensions, albeit at the expense of diminished efficiency and narrower bandwidth. Given that microstrip antennas (also known as patch antennas) are frequently co-fabricated with microwave integrated circuits, an optimal trade-off must be achieved between radiative performance and circuit miniaturization. The radiating patches and feed lines are typically patterned onto the dielectric medium using photolithographic etching techniques [13].

### *Transmission Line Analysis Method*

The transmission-line model represents the most fundamental analytical approach for evaluating microstrip antennas; however, it offers limited precision and adaptability when compared to more advanced modeling techniques. Despite these constraints, the model delivers valuable conceptual understanding of antenna behavior. It idealizes the patch element as a section of a resonant transmission line operating near its half-wavelength ($\lambda/2$) mode to facilitate peak radiation efficiency. While the method is computationally efficient and relatively easy to implement, it lacks the capability to accurately characterize detailed electromagnetic field interactions, including fringing fields and higher-order effects. Additionally, its applicability diminishes in the analysis of complex geometries or when mutual coupling among array elements becomes significant. Nonetheless, the transmission-line formulation remains a practical tool for preliminary microstrip antenna design and serves as a foundational step before applying more rigorous full-wave methods.

In microstrip antenna structures, fringing field behavior is primarily influenced by the aspect ratio of the patch length (L) to the substrate thickness ($h$), denoted as $L/h$, and the substrate's relative permittivity ($\varepsilon r$) [13]. Although fringing effects are inherently minimized when $L/h$ is significantly greater than one, their influence on the resonant frequency remains non-negligible. In microstrip transmission lines, the dominant portion of the electric field is confined within the dielectric substrate, with only a minor portion extending into the surrounding air. When the patch width-to-substrate height ratio ($W/h$) is large, the transverse electric field becomes increasingly concentrated within the substrate material. Under these conditions, the electromagnetic field distribution is predominantly contained within the dielectric, thereby diminishing the extent of edge fringing. This suppression of fringing enhances radiation efficiency and leads to improved

 https://doi.org/ 10.25077/jarpet.v5i1.115

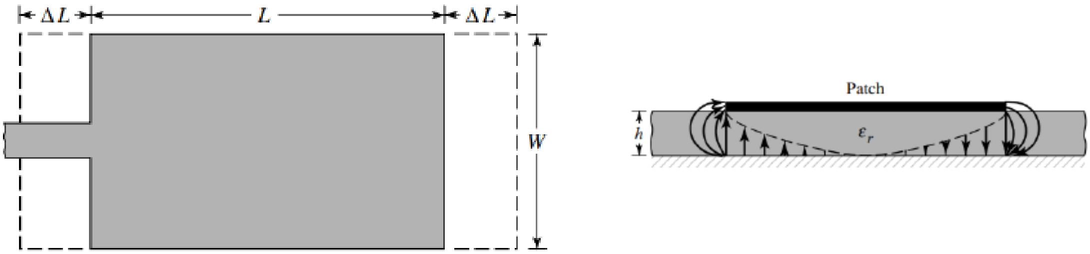
electromagnetic confinement. Since fringing causes the electrical dimensions of the structure to appear larger than their physical size, an effective dielectric constant ($\varepsilon_{reff}$) is introduced to account for this phenomenon. $\varepsilon_{reff}$, which varies with operating frequency, tends to approach the substrate permittivity ($\varepsilon_r$) at higher frequencies due to greater field confinement within the substrate and it can be calculate using (1) [13].

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \tag{1}$$

As a fundamental concept in antenna design, the fringing effect contributes to an increase in the antenna's effective electrical length. This extension, commonly denoted as $\Delta L$, occurs along the radiating edges of the patch. The additional length accounts for the electromagnetic fields that extend beyond the physical boundaries of the patch conductor and must be considered in accurate resonance frequency calculations [13]. $\Delta L$ can be mathematically expressed as (2) and can be drawn in Figure 2. From the additional length, to get the effective L value of the antenna length with the notation using (3) [13].

$$\frac{\Delta L}{h} = \frac{(\varepsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{reff} + 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{2}$$

$$L_{eff} = L + 2\Delta L \tag{3}$$




(a) (b)

Figure 2. Microstrip Antenna; (a) Top view (b) Side view

The effective length ($L_{reff}$) of a microstrip antenna represents the combined length of the physical patch and the additional electrical extension caused by fringing effects [13]. This effective length directly influences the antenna’s resonance characteristics. The resonant frequency is defined as the frequency at which the antenna exhibits minimal reflection coefficient, typically in the range of –10 dB to –20 dB, indicating efficient impedance matching and optimal radiation [13]. The resonant frequency can be mathematically expressed as (4). Additionally, the term characteristic resonant frequency refers to the resonance that occurs when fringing effects cause an increase in the antenna’s effective electrical length. In this context, the physical patch length (L) is replaced by the effective length ($L_{reff}$) to account for the extended field distribution. The characteristic resonant frequency can be determined using (5). From the above equation, the Q-Factor can be derived, defined as the ratio between the characteristic resonant frequency, adjusted for the effective electrical length and the resonant frequency corresponding to the antenna's physical dimensions and can be written as (6). Furthermore, for the dominant mode dimension (L>W>L/2>h) the formula can be denoted as (7).

$$(f_r)_{010} = \frac{1}{2L\sqrt{\varepsilon_r}\sqrt{\mu_0\varepsilon_0}} = \frac{\upsilon_0}{2L\sqrt{\varepsilon_r}} \tag{4}$$

$$(f_{rc})_{010} = \frac{1}{2L_{eff}\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} = \frac{1}{2(L + 2\Delta L)\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} = q\frac{1}{2L\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} = q\frac{\upsilon_0}{2L\sqrt{\varepsilon_r}} \tag{5}$$

$$q = \frac{(f_{rc})_{010}}{(f_r)_{010}} \tag{6}$$

$$(f_r)_{010} = \frac{1}{2W\sqrt{\varepsilon_r}\sqrt{\mu_0\varepsilon_0}} \tag{7}$$

A flat, thin metallic element functions as the primary radiating component for transmitting or receiving electromagnetic waves. This radiating patch is typically designed in simple geometric shapes—such as rectangular, circular, elliptical, triangular, or other forms based on the specific application and design requirements. The shapes of patch shown in Figure 3. The patch is fabricated from highly conductive metals like copper or gold to ensure efficient propagation of electromagnetic energy due to their superior electrical conductivity. The size of the patch depends on the operating frequency of the antenna. The patch length (L) is usually close to half the electromagnetic wavelength in the substrate ($^{\lambda}/_{2}$) for the dominant mode. For the rectangular patch itself, we can find the amount with the formula below, namely W for width and L for length.

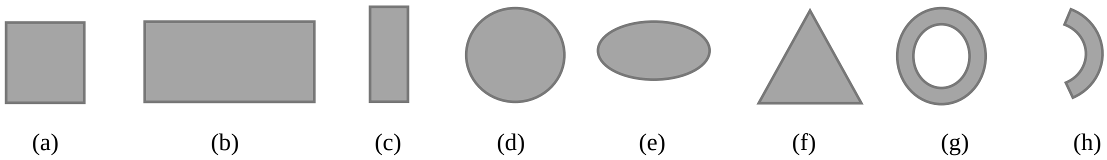



Figure 3. Patch Antenna; (a) Square (b) Rectangular (c) Dipole (d) Circular (e) Elliptical (f) Triangular (g) Circular Ring (h) Ring Sector

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{\upsilon_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{8}$$

$$L = \frac{1}{2f_r\sqrt{\varepsilon_r}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L \tag{9}$$

The substrate in a microstrip antenna is a dielectric layer positioned between the upper conductive patch and the lower ground plane. It plays a critical role in determining the antenna's performance characteristics, such as resonant frequency, radiation efficiency, and bandwidth. The ground plane, located beneath the substrate, acts as an electromagnetic reference and aids in directing the antenna's radiation pattern [14]. Typically, the ground plane dimensions match the substrate in both length and width; however, to ensure proper electromagnetic behavior, the ground plane should extend at least six times the substrate thickness in both dimensions.

$$L_g = L + 6h \tag{10}$$

$$W_g = W + 6h \tag{11}$$

The feedline serves as the transmission path that connects the RF signal source to the radiating patch, facilitating the transfer of radio frequency power to the antenna structure. Among various transmission line types, the microstrip line is widely employed in high-frequency applications, including antenna systems, filters, oscillators, and RF/microwave circuitry. It comprises a conducting strip situated atop a dielectric substrate, with a ground plane positioned beneath. Microstrip-line feeding is a prevalent method in microstrip antenna design due to its fabrication simplicity, ease of impedance matching often achieved through inset adjustment and straightforward analytical modeling. However, increasing the substrate thickness introduces adverse effects, such as the excitation of surface waves and unintended radiation from the feed structure. Surface waves confine energy within the substrate, thereby reducing radiation efficiency, while spurious feedline radiation can lead to interference and degraded antenna performance. These issues inherently limit the achievable bandwidth, which typically remains within the 2–5% range in practical microstrip antenna designs. Consequently, optimizing the trade-offs among substrate thickness, efficiency, and bandwidth is critical in achieving high-performance antenna implementations.

### *The General Parameter of Microstrip Antenna*

Interrelated antenna parameters are essential for evaluating the performance and efficiency of an antenna system. Commonly assessed metrics include return loss, Voltage Standing Wave Ratio (VSWR), operational bandwidth, radiation pattern, and antenna gain [15] [16]. When the input impedance of the antenna is not properly matched to the characteristic impedance of the feedline, reflected waves occur, resulting in standing wave patterns characterized by a ratio of maximum to minimum voltage commonly referred to as the Voltage Standing Wave Ratio (VSWR). In the ideal scenario where there is no reflection (perfect impedance matching), the VSWR equals 1. VSWR value of $\leq 2$ is generally considered acceptable for efficient antenna performance. The VSWR can be calculated using the following (12).

$$VSWR = \frac{|V|_{max}}{|V|_{min}} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{12}$$

Return loss refers to the ratio, expressed in decibels, between the amplitude of the reflected signal and that of the incident signal. This phenomenon arises due to impedance mismatch between the transmission line and the load, which leads to power being reflected back toward the source rather than being fully delivered. In other words, improper impedance matching between the input impedance of the antenna and the characteristic impedance of the feedline results in return loss. A well-matched condition is indicated when the return loss is less than or equal to –10 dB, which can be calculated using (13).

$$Return\ Loss = 20\log|\Gamma| \tag{13}$$

Bandwidth refers to the frequency range over which an antenna or communication system can effectively transmit or receive signals, representing the channel's data-handling capacity. It indicates the volume of information that can be transmitted within a given connection. Bandwidth is typically categorized into two types: broadband and narrowband. Broadband bandwidth is defined as the difference between the upper and lower frequency limits, as expressed in (14). In contrast, narrowband bandwidth is described by (15), where the difference between the highest and lowest frequencies is normalized by dividing it with the antenna's center frequency.

$$BW_{Boardband} = f_H - f_L \tag{14}$$

$$BW_{Boardband} = \left(\frac{f_H f_L}{f_r}\right) \times 100\% \tag{15}$$

Gain represents a quantitative measure of how effectively an antenna converts input power into radio waves directed in a specific direction, reflecting the amplification of the transmitted or received signal relative to the input. It significantly influences the radiation pattern and the antenna's ability to receive signals from particular directions. The gain of an antenna can be determined using (16).

$$G = 4\pi \frac{U(\theta,\phi)}{P_{in}} \tag{16}$$

The quality factor, or Q-factor, is a parameter that characterizes the performance of a resonant structure, including antennas, by quantifying the ratio of stored electromagnetic energy to the energy dissipated due to losses. In antenna systems, the Q-factor reflects the relationship between the energy retained within the radiating structure and the energy lost through radiation, conductor losses, or dielectric dissipation. Specific for microstrip antennas, the Q-factor is typically associated with the resonant bandwidth and the radiation efficiency. The general expression for the Q-factor of an antenna is presented as (17).

$$Q = \frac{f_o}{\Delta f_{\theta 3dB}} \tag{17}$$

The radiation pattern describes the spatial distribution of power radiated or received by an antenna as a function of angle. Represented on a logarithmic scale in decibels (dB), the radiation pattern consists of several components, including the main lobe, side lobes, back lobe, and minor lobes. The main lobe indicates the direction of peak radiation or reception, typically perpendicular to the antenna surface. Side lobes represent secondary peaks adjacent to the main lobe, indicating power radiation in off-axis directions. Minor lobes refer to smaller, less significant radiation in unintended directions, while the back lobe shows radiation in the opposite (180°) direction from the main lobe. An illustrative example of the radiation pattern configuration is provided in Figure 4 [17]. The radiation pattern on the antenna is divided into three types, namely isotropic pattern, directional pattern, and omnidirectional patter.

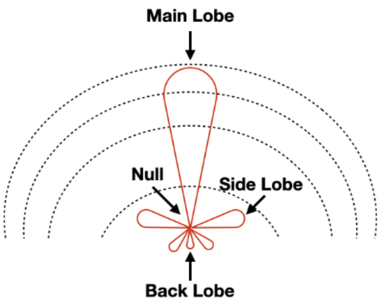



Figure 4. Radiation Pattern

### *Sugar Content*

Substance is defined as a substance composed of discrete particles arranged in specific configurations that determine its physical state. It possesses both mass and volume, occupying physical space. A homogeneous mixture containing two or more substances is referred to as a solution. In such a mixture, the component present in a smaller quantity is termed the solute, while the component in greater quantity is known as the solvent [18]. The concentration of a solution reflects the proportion of solute to solvent and directly influences the solution's physical and chemical properties. Concentration can be expressed in various units, including percentage composition, mole fraction, molarity (M), and molality (m) [18]. Weight percent and volume percent are commonly used for concentration calculations [18]. Mole fraction, denoted by X, is the ratio of the number of moles of a particular component (solute or solvent) to the total number of moles of all constituents in the solution. Molarity, symbolized as M, is defined as the number of moles of solute per liter of solution, or the number of millimoles per milliliter. Molality, represented by m, is the amount of solute in moles per 1000 grams of solvent [18]. The concentration, mole fraction, molarity, and molality written in (18), (19), (20), (21), respectively.

$$Weight\ percent = \frac{gram/vol\ (dissolved)}{gram/vol\ (content)} \times 100\% \quad (18)$$

$$Mole\ Fraction = X_A = \frac{\sum Mole\ A}{\sum Mole\ in\ component} \quad (19)$$

$$Molaritas = \frac{Mole\ of\ dissolved\ substance}{liter\ (content)} \quad (20)$$

$$Molality = \frac{Mole\ of\ dissolved\ substance}{Kg\ (content)} \quad (21)$$

### *Dielectric Constant*

Dielectric constant, also known as relative permittivity and symbolized as $\varepsilon_r$, quantifies a material's capacity to retain electrical energy under an applied voltage. It reflects how much electric field a dielectric material can support compared to vacuum. This constant is derived through a specific mathematical relationship [19]. Any variation in the dielectric constant within a material directly influences its capacitance. The insertion of a dielectric substance between the plates of a capacitor modifies the electric field distribution, resulting in a change in capacitance. This effect occurs due to the alteration of the electric potential across the parallel plates. The resulting capacitance, when a dielectric is present between the plates, can be calculated using the appropriate theoretical expression [19].

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \quad (14)$$

$$C = k\varepsilon_0 \frac{A}{d} \quad (15)$$

### *Antenna for Sugar Content Detection*

In wireless communication systems, antennas are conventionally employed for transmitting and receiving electromagnetic signals. Nevertheless, antennas can also be adapted for sensing purposes by exploiting the interaction of electromagnetic waves with materials. As demonstrated in previous studies [20], antenna-based sensors can be utilized to detect variations in salt and sugar concentrations in aqueous solutions. This sensing mechanism operates by monitoring changes in the dielectric properties of the solution, which are directly influenced by its composition. Specifically, the dielectric constant decreases as the concentration of dissolved salts or sugars increases, due to the corresponding reduction in water content. The introduction of salt into water modifies its dielectric behavior by increasing the number of dissolved ions, which interact with water molecules and suppress dipole polarization. This results in a decline in both the dielectric constant and the dielectric loss factor [21]. Similarly, when sugar is dissolved, it forms hydrogen bonds with water molecules, further diminishing the dipolar response and consequently lowering the dielectric constant. A decrease in dielectric constant leads to an increase in load impedance and a corresponding rise in the reflection coefficient [1].

## RESULTS AND DISCUSSION

The antenna under investigation was designed as a rectangular microstrip patch structure intended for wireless communication applications. The antenna was implemented on a dielectric substrate with known electrical properties including relative permittivity, thickness, and loss tangent. The patch dimensions were determined analytically based on the transmission line model, taking into account effective dielectric constant and fringing effects at the radiating edges. The specification antenna shown in Table 1 and the design of pre-optimization shown in Figure 5.

Table 1. Specification antenna

| **Specification** | **Value** |
|---|---|
| Resonant frequency | 2.4 GHz |
| Substrate height | 1.6 mm |
| Patch height | 0.035 mm |
| Relative permittivity | 4.3 |
| Characteristic impedance | 50 Ω |

 https://doi.org/ 10.25077/jarpet.v5i1.115

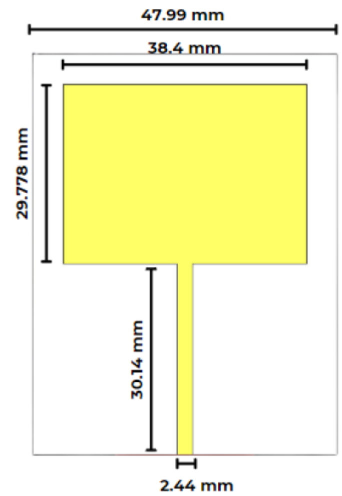


Figure 5. Pre-Optimization Design of Antenna

Using the formulas in the theoretical basis and optimizing the antenna parameters, the antenna design below is obtained with the values as listed in the parameter list. The antenna is made of two materials: pure copper and FR-4 substrate. Antenna design after optimization using software shown in Figure 6. The relative dielectric constant of sugar was taken from a journal following an experiment from one of the journals as in the theoretical basis. The design namely sugar content with a relative dielectric constant of 0.075. The design shown in Figure 7.

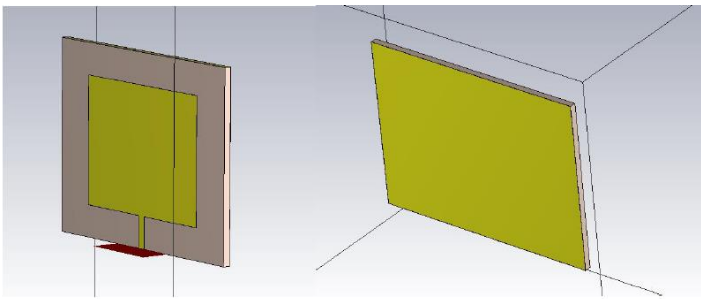


Figure 6. Pre-Optimization Design of Antenna

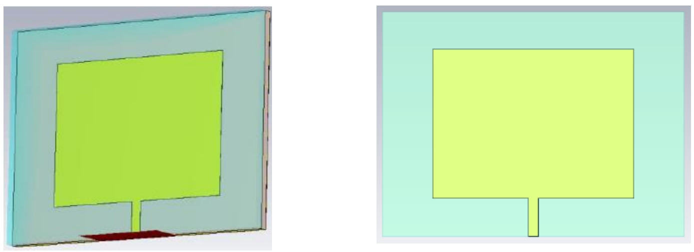


Figure 7. Design Antenna of Sugar Content

The analysis obtained for the previous design based on the VSWR value before the antenna was added with sugar solution can be seen in the graph below, where the VSWR value at 2.4GHz is 1.62. The graphic of VSWR value shown in Figure 8. The reflection coefficient value with a resonant frequency of 2.4 GHz is -12.51dB, meeting the standard value of reflection coefficient for microstrip antennas and its shown in Figure 9. The Q-factor after calculation value is 35.2853.

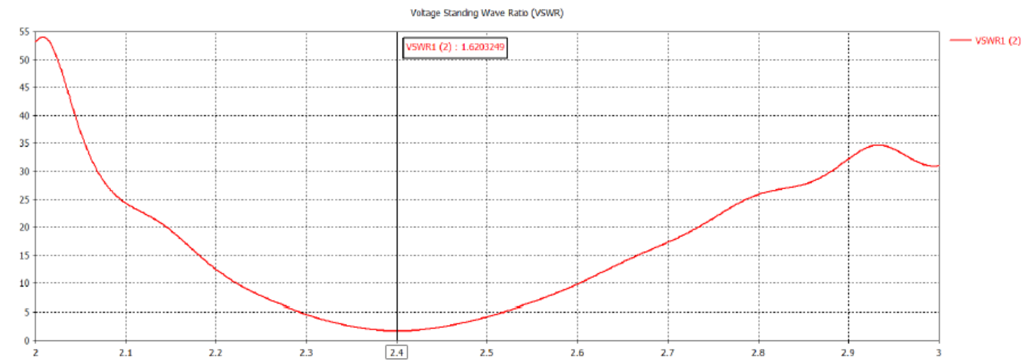


Figure 8. VSWR value

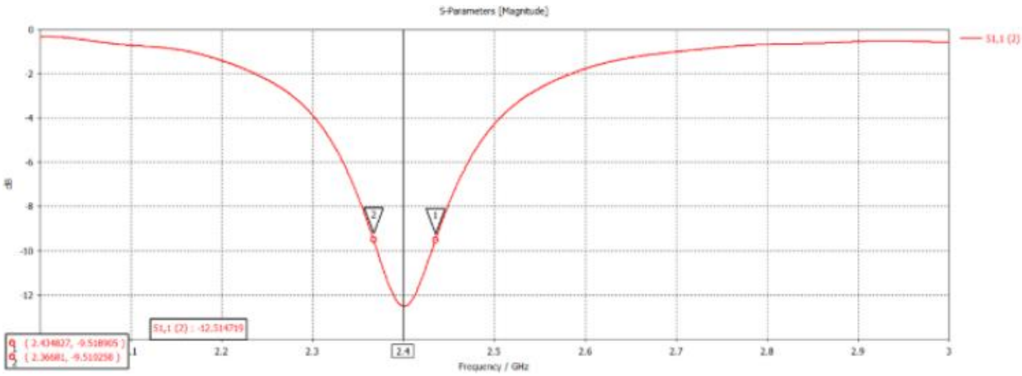


Figure 9. Reflection coefficient value

After testing with sugar content, the VSWR value of the antenna after adding sugar content is shown in Figure 10, where the VSWR value at 2.4 GHz is 1.375. the reflection coefficient value with a resonant frequency of 2.4 GHz is -16.014 dB, fulfilling the standard reflection coefficient value for microstrip antenna. The Q-factor after calculation value is 110.02.

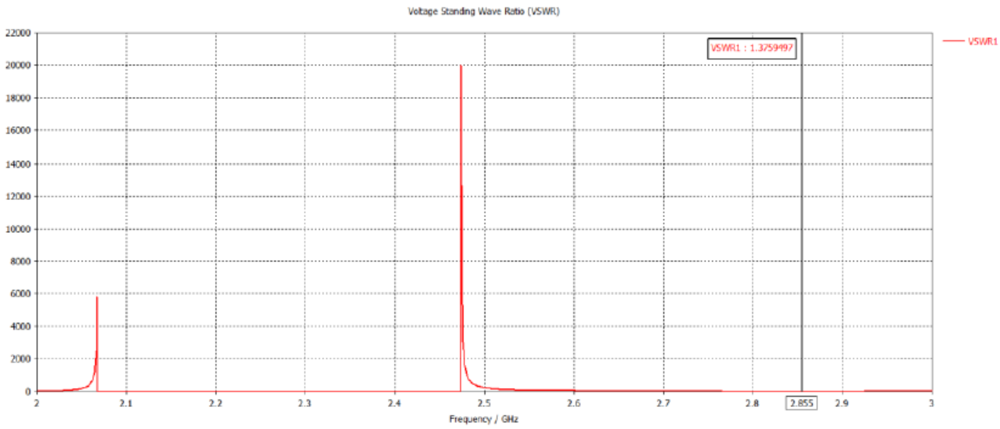


Figure 10. VSWR value after testing with sugar content

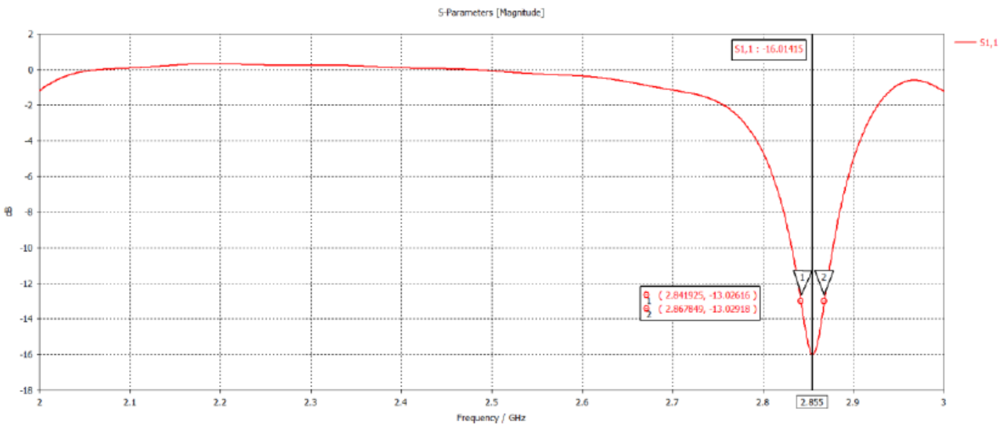


Figure 10. Reflection coefficient value after testing with sugar content

The observed shift in the resonance frequency ($f_r$) of the rectangular microstrip patch antenna from 2.4 GHz to 2.855 GHz, induced by the introduction of a sucrose solution with a molar fraction of 0.075, indicates a significant alteration in the antenna's electromagnetic characteristics. This rightward frequency shift of approximately 400 MHz is directly attributed to variations in the effective dielectric constant ($\varepsilon_{eff}$), which is influenced by both the intrinsic properties of the substrate and the surrounding medium. The $\varepsilon_{eff}$, which governs the electromagnetic wave propagation within the patch structure, is generally expected to increase in the presence of a high-dielectric-constant medium such as a sugar solution, resulting in a lower resonance frequency. However, the observed upward shift in $f_r$ suggests the involvement of additional factors, such as modifications in energy dissipation, altered boundary conditions, or changes in the electromagnetic field distribution over the patch.

The structural interaction between the sugar solution and the patch antenna not only affects the $f_r$ but also has ramifications on other critical performance metrics, including the Voltage Standing Wave Ratio (VSWR), quality factor (Q-factor), and reflection coefficient ($S_{11}$). The VSWR, which quantifies impedance matching between the antenna and the transmission line, is likely impacted due to the emergence of a new impedance imbalance introduced by the dielectric variation. Likewise, the Q-factor, representing the ratio of stored to dissipated energy within the antenna system, may either improve or deteriorate depending on how the dielectric loading influences substrate losses and radiative efficiency. Furthermore, the $S_{11}$, indicative of the proportion of incident power reflected back toward the source, is also modulated by the altered dielectric environment. The presence of the sucrose solution potentially distorts the radiation pattern and reduces radiation efficiency, which in turn affects the minimum $S_{11}$ value and the frequency at which optimal impedance matching is achieved. Consequently, the antenna may exhibit reduced efficiency at its original design frequency of 2.4 GHz while exhibiting enhanced performance at the new resonance frequency of 2.855 GHz.

In summary, this analysis underscores that the interaction between a sugar-based dielectric medium and the microstrip antenna structure considerably influences the antenna's operational behavior. The shift in resonance frequency, along with the variations in VSWR, Q-factor, and $S_{11}$, are symptomatic of fundamental changes in the electromagnetic field configuration and dielectric loading. Further investigation is warranted to thoroughly understand these effects, including their impact on radiation parameters such as gain, efficiency, and radiation pattern. This understanding is essential for practical deployment, especially in scenarios where the antenna may be exposed to dielectric perturbations such as sugar-based solutions.

## CONCLUSIONS

The addition of sugar solution with a mole fraction of 0.075 to a rectangular patch microstrip antenna causes a shift in the resonant frequency ($f_r$) from 2.4 GHz to 2.855 GHz, reflecting a significant change in the effective dielectric constant ($\varepsilon_{eff}$) of the antenna. This shift also has an impact on other operational parameters, such as VSWR, Q-factor, and $S_{11}$ parameter, indicating a change in the antenna structure and the interaction of the surrounding electromagnetic field. A change in the VSWR value indicates a new imbalance in the antenna's impedance matching, while a change in the $S_{11}$ value indicates an adjustment of the antenna's radiation pattern and efficiency to the new frequency. The Q-factor value, which is related to the energy efficiency of the antenna, is also affected by the energy dissipation effect that occurs due to the addition of sugar solution. These results show that the dielectric environment around the antenna greatly affects the performance of the microstrip antenna, both in terms of operational frequency and radiation characteristics. Therefore, a deeper understanding of the effects of external materials on microstrip antennas is essential, especially for practical applications where the antenna may be exposed to certain materials. This analysis provides important insights for the design of antennas that are more adaptive to environmental changes.

## REFERENCES


[1] Sandhu, S., Naz, S., Ejidike, I. P., & Ata, A. (2025). Carbohydrates: Classification and Biosynthesis. In Synthesis and Applications of Carbohydrates, Lipids, and Steroids (pp. 333-342). CRC Press.

[2] Devi, N. (2024). Chapter-2 Biomolecules: General Concepts. Dr. Navjot Singh Sethi, 25.

[3] Prada, M., Saraiva, M., Garrido, M. V., Sério, A., Teixeira, A., Lopes, D., ... & Rodrigues, D. L. (2022). Perceived associations between excessive sugar intake and health conditions. Nutrients, 14(3), 640.

[4] Janssen, J. A. (2021). Hyperinsulinemia and its pivotal role in aging, obesity, type 2 diabetes, cardiovascular disease and cancer. International journal of molecular sciences, 22(15), 7797.

[5] Bakam Nguenouho, O. S., Chevalier, A., Potelon, B., Benedicto, J., & Quendo, C. (2022). Dielectric characterization and modelling of aqueous solutions involving sodium chloride and sucrose and application to the design of a bi-parameter RF-sensor. Scientific Reports, 12(1), 7209.

[6] Hua, Y., Hao, Y., & Zhang, X. (2024). Prediction of the apple sugar content of multiple varieties by dielectric spectroscopy. Journal of the ASABE, 67(3), 785-796.

[7] C. A. Balanis, Antenna Theory Analysis and Design, 3rd ed. 2005.

[8] Hakim, R.I., Mahendra, D., & Endarko. (2023). Vivaldi Tapered Slot Antenna for Microwave Imaging in Medical Application. Jurnal Teknik Elektro,15(2), 2023.

[9] El Gharbi, M., Martinez-Estrada, M., Fernandez-Garcia, R., & Gil, I. (2021). Determination of salinity and sugar concentration by means of a circular-ring monopole textile antenna-based sensor. IEEE Sensors Journal, 21(21), 23751-23760.

[10] Costanzo, A., Augello, E., Battistini, G., Benassi, F., Masotti, D., & Paolini, G. (2023). Microwave devices for wearable sensors and IoT. Sensors, 23(9), 4356.

[11] Ramadhamy, Q. H., Pramudita, A. A., & Suratman, F. Y. (2023, July). Clutter Reduction in Detecting Trapped Human Respiration Under Rubble for FMCW Radar System. In 2023 International Seminar on Intelligent Technology and Its Applications (ISITIA) (pp. 716-721). IEEE.

[12] Anchidin, L., Lavric, A., Mutescu, P. M., Petrariu, A. I., & Popa, V. (2023). The design and development of a microstrip antenna for internet of things applications. Sensors, 23(3), 1062.

[13] Delanerolle, G., Ayis, S., Barzilova, V., Phiri, P., Jagadeesan, P., Zeng, Y., Hapangama, D. K. (2025). Systematic review and meta-analysis of polycystic ovary syndrome and mental health among Black Asian Minority Ethnic populations. Academia Mental Health and Well-Being, 2(1). https://doi.org/10.20935/MHealthWellB7404

[14] Jaf, Saba F. Ahmed., Kanaan, Amenah Edress. (2025). High-Gain Microstrip Patch Antenna Using Artificial Magnetic Conductor Structure. Academia Open Universitas Muhammadiyah Siduarjo, 10(1). https://doi.org/10.21070/acopen.10.2025.10880

[15] Yahya Albaihani, Rizwan Akram, Ziyad Almohaimeed, Abdullah Almohaimeed, El Amjed Hajlaoui. (2025). Optimal antenna design for wireless energy harvesting system in ISM band, 73. https://doi.org/10.1016/j.rinp.2025.108255

[16] Saravanakumar, R & Raja, Arumalla & Narayan, Puneet & Rajesh, Gangolu & Vinoth, M. & Thommandru, Raju. (2024). Dual-Band Performance Enhancement of Square Wheel Antennas with FR4 Substrate for Sub 7GHz Applications. 1-7. 10.1109/ACROSET62108.2024.10743604.

[17] Valerie. (2024). How to Interpret Antenna Radiation Patterns. 5G Store.

[18] Abozenadah, H., Bishop, A., & Bittner, S. (2018). CH104: Chemistry and the Environment - Chapter 7: Solutions. Western Oregon University.

[19] Sebastian, M. T. (2008). Chapter two – Measurement of microwave dielectric properties and factors affecting them. In M. T. Sebastian (Ed.), Dielectric materials for wireless communication (pp. 11–47). Elsevier. https://doi.org/10.1016/B978-0-08-045330-9.00002-9

[20] Islam, Mohammad & Rahman, Md & Mandeep, J. & Samsuzzaman, Md. (2018). Detection of Salt and Sugar Contents in Water on the Basis of Dielectric Properties Using Microstrip Antenna-Based Sensor. IEEE Access. PP. 1-1. 10.1109/ACCESS.2017.2787689.

[21] Ellison, Candice & Mckeown, Murat & Trabelsi, Samir & Marculescu, Cosmin & Boldor, Dorin. (2018). Dielectric characterization of bentonite clay at various moisture contents and with mixtures of biomass in the microwave spectrum. Journal of Microwave Power and Electromagnetic Energy. 1-13. 10.1080/08327823.2017.1421407.

[22] M. T. Islam, M. N. Rahman, M. S. J. Singh and M. Samsuzzaman, "Detection of Salt and Sugar Contents in Water on the Basis of Dielectric Properties Using Microstrip Antenna-Based Sensor," in IEEE Access, vol. 6, pp. 4118-4126, 2018, doi: 10.1109/ACCESS.2017.2787689