

A Novel Compact High-Gain Decagonal Microstrip Antenna for Soil Moisture Sensing via Resonant Frequency Shift

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ABSTRACT: This paper presents the design, fabrication, and experimental validation of a novel compact high-gain decagonal microstrip patch antenna designed for noninvasive soil moisture sensing. The antenna utilizes the strong correlation between its dielectric properties and soil moisture content, which directly influences its reflection coefficient and resonant frequency. The decagonal geometry using a Taconic TLY-5 substrate achieved a high gain of 7 dBi and an excellent radiation efficiency of 96.5% compared to the FR-4 substrate. The prototype antenna fabricated on a Taconic TLY-5 substrate resonates at a frequency of 2.445 GHz with a measured reflection coefficient of -34.3 dB, validating the high-performance characteristics predicted by full-wave simulations using CST Studio Suite 2018. The sensing capability of the fabricated antenna is carefully tested across sandy, loamy, and clayey soils, demonstrating a predictable downward shift in the resonant frequency as the moisture content increased. A linear regression analysis was performed on the experimental data from sandy, loamy, and clayey soils, yielding a high coefficient of determination ($R^2 \approx 0.9$) for all three soil types and establishing a calibration model to accurately convert the resonant frequency shifts into soil moisture values. The obtained sensitivity values for soil moisture detection were 4.76 MHz/% for sandy soil, 5.15 MHz/% for loamy soil, and 4.89 MHz/% for clayey soil. The compact size, high gain, and consistent performance across different soil samples make this proposed antenna a better solution for precision agriculture and environmental monitoring through integration into wireless sensor networks.

1. INTRODUCTION

Soil moisture monitoring is critical for efficient water resource management and environmental monitoring in modern precision agriculture [1]. Optimizing irrigation, increasing crop yields, and reducing the effects of drought depend on precise and timely measurements of soil moisture content. Conventionally, soil moisture is measured using a gravimetric technique, which is highly accurate, destructive, and unsuitable for real-time applications [2]. Although conventional soil moisture sensors, such as capacitive, resistive, time domain reflectometry (TDR), and frequency domain reflectometry (FDR) probes, are capable of providing real-time soil moisture data, they possess certain inherent limitations. Despite their low cost, resistive sensors exhibit poor stability, low accuracy, and susceptibility to corrosion and soil salinity. As capacitive sensors are sensitive to temperature, salinity, and soil type, precise calibration of soil-specific calibration is required to achieve an acceptable accuracy [3]. TDR and FDR sensors [4] are more precise, but their high cost, complicated setup and operation, high power consumption, and sensitivity to soil salinity render them unsuitable for widespread and economical applications. This has motivated research into nondestructive approaches, especially microwave sensing, which provides the benefits of real-time monitoring, nondestructive nature, and the possibility of distributed sensing via wireless sensor networks. Conventional sensors depend on the direct contact between the electrodes

and soil, which makes their performance sensitive to corrosion and temperature-induced drift. In contrast, microstrip antenna-based sensors use resonant frequency shifts to detect the dielectric properties of soil [5].

Soil can be modelled as a heterogeneous three-phase medium composed of soil, water, and air [6]. Because each phase has unique dielectric characteristics, the volumetric fractions and interaction mechanisms of each phase define the effective complex permittivity of soil. Dielectric-based soil moisture sensing depends on the intrinsic electromagnetic contrast within the soil-water-air system, where water exhibits a higher relative permittivity at microwave frequencies than soil minerals and air. As the water content increased, the permittivity of the soil increased significantly, influencing the propagation, reflection, and resonance of electromagnetic waves within the medium. Owing to dielectric sensitivity, the microstrip antenna used to measure soil moisture content can detect resonant frequency shifts or changes in the reflection coefficient [7]. Therefore, the dielectric properties of the soil directly couple with the electromagnetic behavior of the microstrip antenna sensor, enabling non-contact, resonance-based measurement of soil moisture through soil-sensor interactions. Microwave sensing uses a two-step physical method to retrieve soil moisture. The complex dielectric constant (CDC) of the soil was first calculated using the radiation signal received by the sensor. Second, the moisture is obtained by soil complex dielectric constant models, which include the complex relationship between soil moisture and its CDC [8]. The Topp empirical model provides a linear

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relationship between the real part of the soil permittivity and the volumetric water content. Accordingly, variations in soil moisture modify the effective permittivity of the medium, resulting in measurable shifts in the resonant frequency of the antenna.

Microstrip antennas have gained popularity in microwave-based sensing applications due to their small size, low profile, ease of fabrication, and low cost [9–11]. The resonant frequency of a microstrip antenna is highly sensitive to its dielectric properties [12], making it an excellent option for soil moisture sensing. When the antenna is in proximity to soil, variations in the moisture content modify the soil's dielectric constant, causing a noticeable shift in the antenna's resonance frequency [13] and reflection coefficient. The performance of this microstrip antenna sensor is influenced by the properties of the dielectric constant and loss tangent of the substrate, which affect antenna efficiency and gain [14]. Owing to the heterogeneous nature of the soil and fringing-field interactions, the frequency response of the antenna-soil system deviates from a straightforward analytical form. Consequently, a regression model was employed to provide an effective empirical relationship between the sensor's measurable resonant frequency shift and gravimetric water content of the soil.

The primary goal of this study was to design and evaluate a compact decagonal microstrip antenna that employs the frequency shift method as a sensitive soil moisture sensor. Additionally, it aims to experimentally establish a reliable correlation between frequency and moisture for accurate estimation of water content. Focusing on the potential of microstrip antennas for sensing applications, this study first investigated the influence of the substrate material on the overall antenna performance. Specifically, FR-4 and Taconic TLY-5 substrates were used to design a decagonal microstrip patch antenna (DMPA) operating at a resonant frequency of 2.45 GHz. The decagonal patch geometry of the proposed antenna lowers the reflection coefficient, and the Taconic TLY-5 substrate enhances the gain and radiation efficiency. This DMPA is very useful for practical sensing applications because it achieves a high gain of 7 dBi and an excellent radiation efficiency of 96.5%. The experimental results demonstrate the capability of the antenna to accurately detect variations in the soil moisture content by observing shifts in the resonant frequency, highlighting its practical applications.

The remainder of this paper is organized as follows. The antenna design and its simulation methodology are thoroughly described in Section 2, and Section 3 presents the experimental setup for soil moisture sensing. The experimental results, regression analysis, and associated discussions are presented in Section 4. Finally, Section 5 concludes the paper with a summary of the findings.

2. ANTENNA DESIGN AND SIMULATION METHODOLOGY

Microstrip patch antennas are widely used because of their low profile, light weight, and ease of integration with microwave circuits. A typical microstrip antenna consists of a metallic radiating patch on one side of a dielectric substrate, and a ground plane on the opposite side [15]. The proper selection of sub-

strate material has a significant impact on antenna performance, influencing its size, gain, and radiation efficiency. The proposed antenna is designed using FR-4 and Taconic TLY-5 substrates, which have dielectric constants of 4.3 and 2.2 and low loss tangents of 0.02 and 0.0009, respectively. This antenna is designed at a resonant frequency of 2.45 GHz, which is widely used for Industrial, Scientific, and Medical (ISM) applications. The design of the proposed antenna comprises a decagonal radiating patch of radius a in mm, given by Equation (1) [16], on top of the substrate.

$$a = \frac{F}{\left\{1 + \frac{2h}{F\pi\epsilon_r} \left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{\frac{1}{2}}} \quad (1)$$

$$F = \frac{8.791 \times 10^9}{f_r \sqrt{\epsilon_r}} \quad (2)$$

where h denotes the substrate thickness in mm, ϵ_r the relative dielectric constant of the substrate, and f_r the resonant frequency in GHz.

By employing a decagonal radiator with an inset feed, the design achieves a lower reflection coefficient and resonance at the desired frequency compared with traditional rectangular or circular patches while retaining a compact form factor. To achieve impedance matching, a 50Ω microstrip feedline with length L_f and width W_f was connected to the patch using an inset feed with depth L_i and width W_i . The detailed geometry of the proposed DMPA is illustrated in Figure 1. Using the optimum design parameters given in Table 1, the performance of the proposed DMPA on both FR-4 and Taconic TLY-5 substrates was analyzed using CST Studio Suite 2018 electromagnetic simulation software.

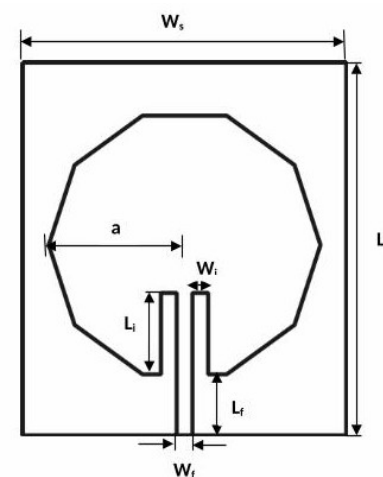


FIGURE 1. Decagonal microstrip patch antenna layout.

3. ANTENNA FABRICATION AND EXPERIMENTAL SETUP

3.1. Fabrication and Characterization

The prototype of the proposed antenna was fabricated using a standard printed circuit board (PCB) fabrication method on a

TABLE 1. Dimensions of the proposed antenna geometry.

| Parameters | | Dimensions (mm) | |
|--------------------------|-------|-----------------|---------------|
| | | FR-4 | Taconic TLY-5 |
| Patch | a | 18 | 25.05 |
| Substrate & Ground plane | W_s | 43.16 | 59.63 |
| | L_s | 53.16 | 68.63 |
| | h | 1.6 | 1.588 |
| Feedline | W_f | 3 | 3 |
| | L_f | 10 | 10 |
| Inset | W_i | 3 | 3 |
| | L_i | 15 | 15 |

high-performance Taconic TLY-5 substrate with the parameters listed in Table 1. A photograph of the prototype is shown in Figure 2.

The reflection coefficient (S_{11}), resonant frequency (f_r), input impedance (Z_{11}), and Voltage Standing Wave Ratio (VSWR) of the fabricated antenna were measured using a vector network analyzer (VNA) (FPC 1500, 5 kHz–3 GHz, R&S made). To ensure the measurement accuracy, the VNA was first calibrated at the reference plane of the coaxial cable connected to the antenna, using calibration kits.

3.2. Soil Moisture Sensing Procedure

The resonance frequency of the antenna is highly sensitive to the dielectric properties of its surroundings. When the antenna is in contact with soil, variations in the soil moisture content modify the dielectric constant [17], which causes a measurable shift in the resonance frequency of the antenna. Compared to the air and dry soil components, water has a substantially larger dielectric constant. Consequently, the total effective dielectric constant of the soil increased with the moisture content. The relationship between the dielectric constant of the soil ϵ_{soil} and the resonant frequency f_r of the antenna [18] is given by Equation (3). The moisture content of the soil can be accurately determined by measuring the shift in resonance frequency.

$$f_r \propto \frac{1}{\sqrt{\epsilon_{soil}}} \quad (3)$$

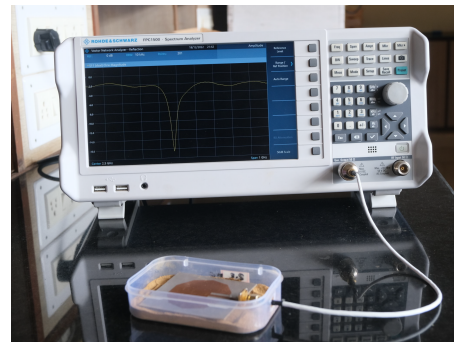
Sandy, loamy, and clayey soil samples were collected from Ujire, Karnataka. The soil samples were dried and sieved to remove large particles. The prepared samples were dried using a hot-air oven at 105°C for 24 h to remove residual moisture. Initially, 50 g of each dry soil sample was taken, and then, the antenna was placed directly on the surface of the soil to measure the resonant frequency of the fabricated antenna using the VNA. Subsequently, controlled amounts of water were added incrementally to each soil sample to obtain samples with varying moisture contents. For each sample, the moisture content was determined using the gravimetric method, based on the weights of wet and dry soil, as defined in Equation (4) [19].

$$MC(\%) = \frac{W_w - W_d}{W_d} \times 100 \quad (4)$$

**FIGURE 2.** Proposed antenna prototype.

where MC denotes the percentage of moisture content, W_w the weight of the wet soil sample in grams, and W_d the weight of the dry soil after oven-drying in grams.

The changes in the resonant frequency of the proposed antenna, corresponding to each soil sample at different moisture levels, were recorded using VNA. The experimental setup used for soil moisture sensing is shown in Figure 3.

**FIGURE 3.** Experimental setup for soil moisture sensing.

4. RESULTS AND DISCUSSION

This section presents the results obtained from simulations carried out using the Computer Simulation Technology (CST) Studio Suite 2018 electromagnetic (EM) simulation software, along with experimental measurements obtained from the VNA. A comparison between the simulated and measured data is provided to evaluate the performance of the antenna, followed by a detailed discussion of the soil moisture sensing results across different soil types using linear regression analysis.

4.1. Simulated Antenna Results

The simulation results highlight the influence of the substrate material on the performance of the proposed antenna, validating the choice of a low-permittivity substrate for soil moisture sensing applications. A comparative analysis was performed between FR-4 and Taconic TLY-5 substrates to evaluate their performance characteristics. Figure 4 shows the simulation re-

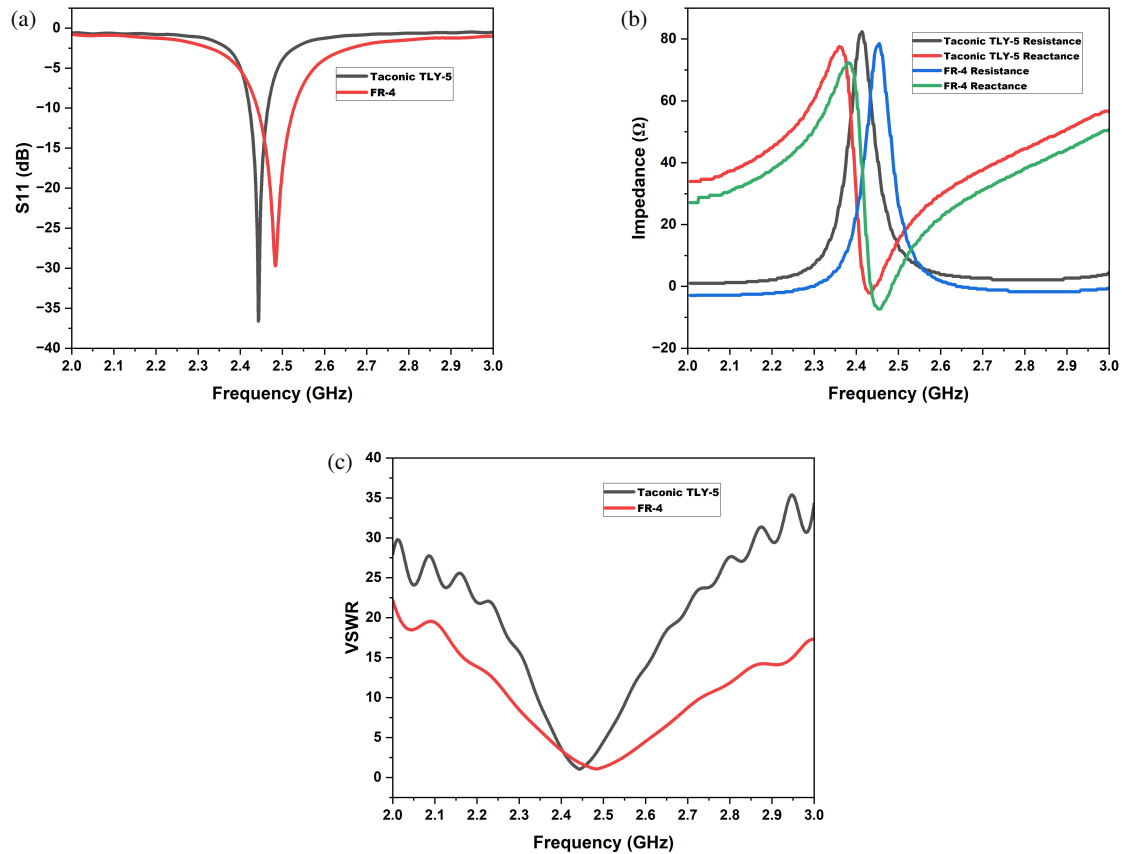


FIGURE 4. Simulated characteristics of proposed antennas: (a) Reflection coefficient, (b) input impedance, (c) VSWR.

sults of S_{11} , the input impedance, and the VSWR of the proposed antenna designs. The gain and radiation efficiencies of these designs are shown in Figure 5. Table 2 provides a comparative summary of their performances.

TABLE 2. Simulated results of proposed antenna using FR4 and Taconic TLY-5 substrates.

| Parameters | FR-4 | Taconic TLY-5 |
|------------------------------|-----------------|-----------------|
| Resonant frequency (GHz) | 2.483 | 2.443 |
| Reflection coefficient (dB) | -29.71 | -36.62 |
| Input Impedance (Ω) | $45.48 + j0.49$ | $49.32 + j0.17$ |
| VSWR | 1.07 | 1.03 |
| Gain (dBi) | 2.8 | 7 |
| Radiation efficiency (%) | 49.74 | 96.89 |

As shown in Table 2, the FR-4 substrate-based decagonal microstrip patch antenna design resonated at a frequency of 2.483 GHz with a minimum reflection coefficient of -29.71 dB. In contrast, the DMPA designed using a Taconic TLY-5 substrate exhibits a resonance at 2.443 GHz frequency with a minimum S_{11} of -36.62 dB, indicating improved impedance matching and reduced reflection. The Taconic TLY-5 substrate antenna achieved a simulated voltage standing

wave ratio (VSWR) of 1.03 at resonance, demonstrating excellent impedance matching with minimal reflected power. The FR-4 antenna exhibited 1.07 VSWR, indicating comparatively higher substrate losses. The simulated input impedance results show a distinct difference between the two substrates, with the FR-4 antenna having a real impedance of 45.48Ω and a slightly inductive imaginary impedance of $j0.47 \Omega$ at resonance, while the Taconic TLY-5 substrate-based antenna exhibits a nearly perfect match with a real impedance of 49.32Ω and a minimal inductive imaginary impedance of $j0.17 \Omega$, indicating its superior performance.

The simulated peak gain for the Taconic TLY-5 substrate-based antenna is 7 dBi, which is substantially higher than the 2.8 dBi observed for the FR-4 substrate. Similarly, the radiation efficiency of the Taconic TLY-5 substrate antenna was 96.89%, whereas the FR-4 counterpart achieved only 49.74% efficiency. The significantly lower loss tangent ($\tan \delta = 0.0009$) of the Taconic TLY-5 substrate minimizes energy dissipation within the substrate. This reduction in dielectric loss allows a greater proportion of the input power to be converted into radiated power, thereby increasing the radiation efficiency and enhancing the antenna gain. By achieving a high gain, the proposed antenna with a Taconic TLY-5 substrate facilitates deeper electromagnetic field penetration into the soil medium. Therefore, this antenna is well-suited for soil moisture sensing applications in precision agriculture.

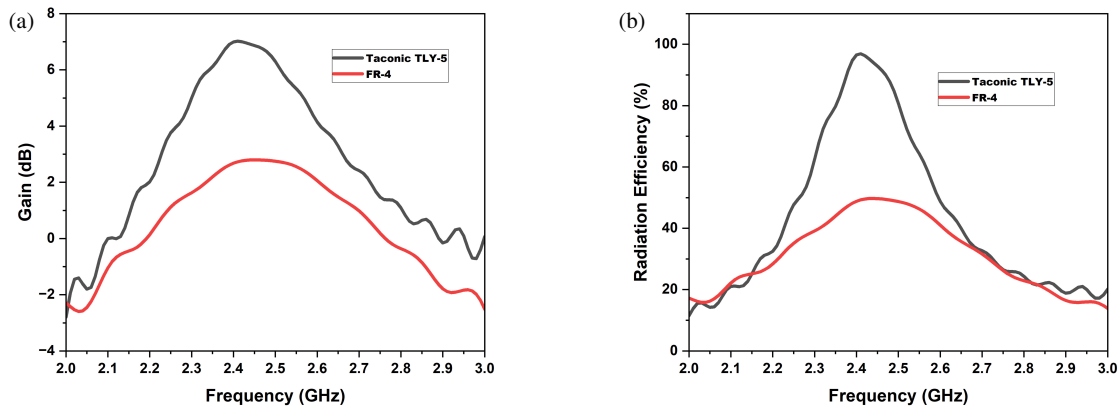


FIGURE 5. Simulated characteristics of proposed antennas: (a) Gain, (b) radiation efficiency.

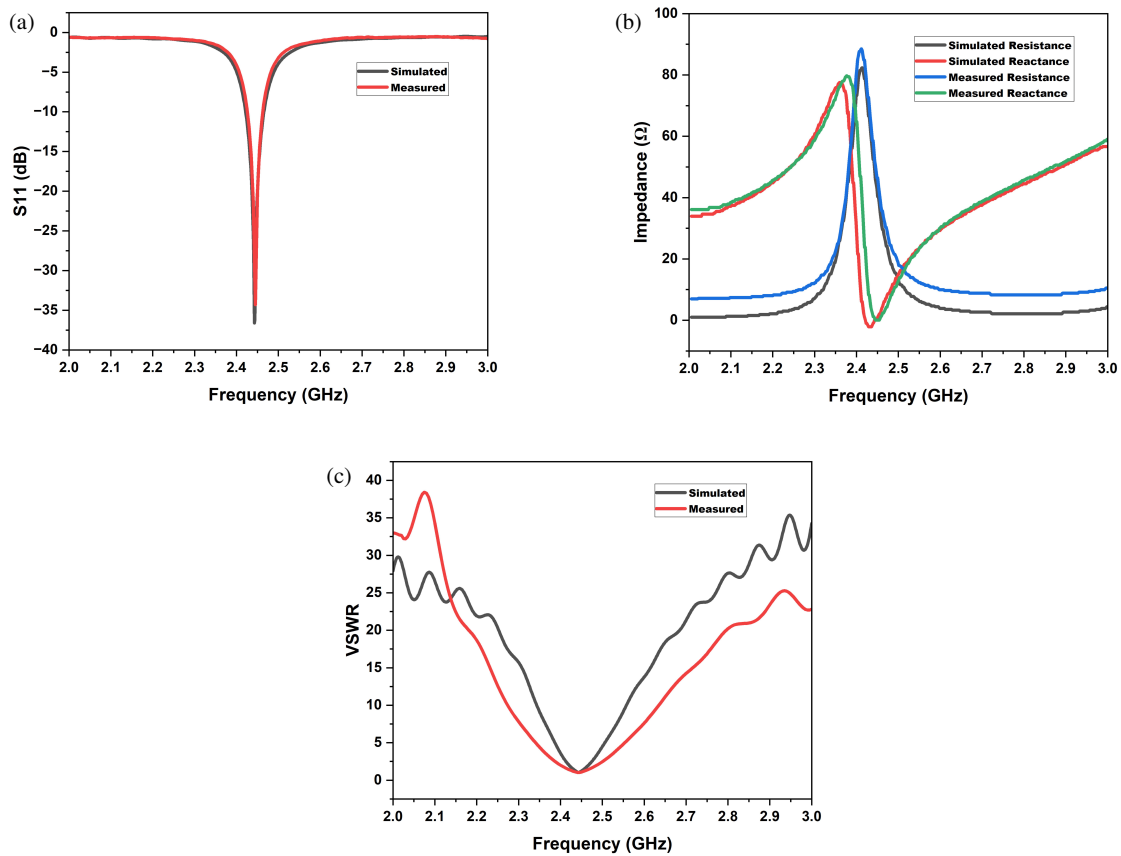


FIGURE 6. Characteristics of Taconic TLY-5 antenna: (a) Reflection coefficient, (b) input impedance, (c) VSWR.

4.2. Experimental Verification and Comparative Results

The performance characteristics of the fabricated decagonal microstrip antenna on a Taconic TLY-5 substrate were measured to validate the simulated results. The reflection coefficient, resonant frequency, input impedance, and VSWR of the prototype antenna were measured using a Vector Network Analyzer and are presented in Figure 6, together with the corresponding simulated results obtained from CST Studio Suite 2018 for comparison. A comparative summary of the simulated and measured performance parameters of the prototype antenna is given in Table 3.

TABLE 3. Simulated and measured results of proposed Taconic TLY-5 antenna.

| Parameters | Simulated | Measured |
|------------------------------|-----------------|------------------|
| Resonant frequency (GHz) | 2.443 | 2.445 |
| Reflection coefficient (dB) | -36.62 | -34.3 |
| Input Impedance (Ω) | $49.32 + j0.17$ | $50.47 + j0.074$ |
| VSWR | 1.03 | 1.02 |

The measured prototype parameters, including the resonant frequency, reflection coefficient, VSWR, and input impedance,

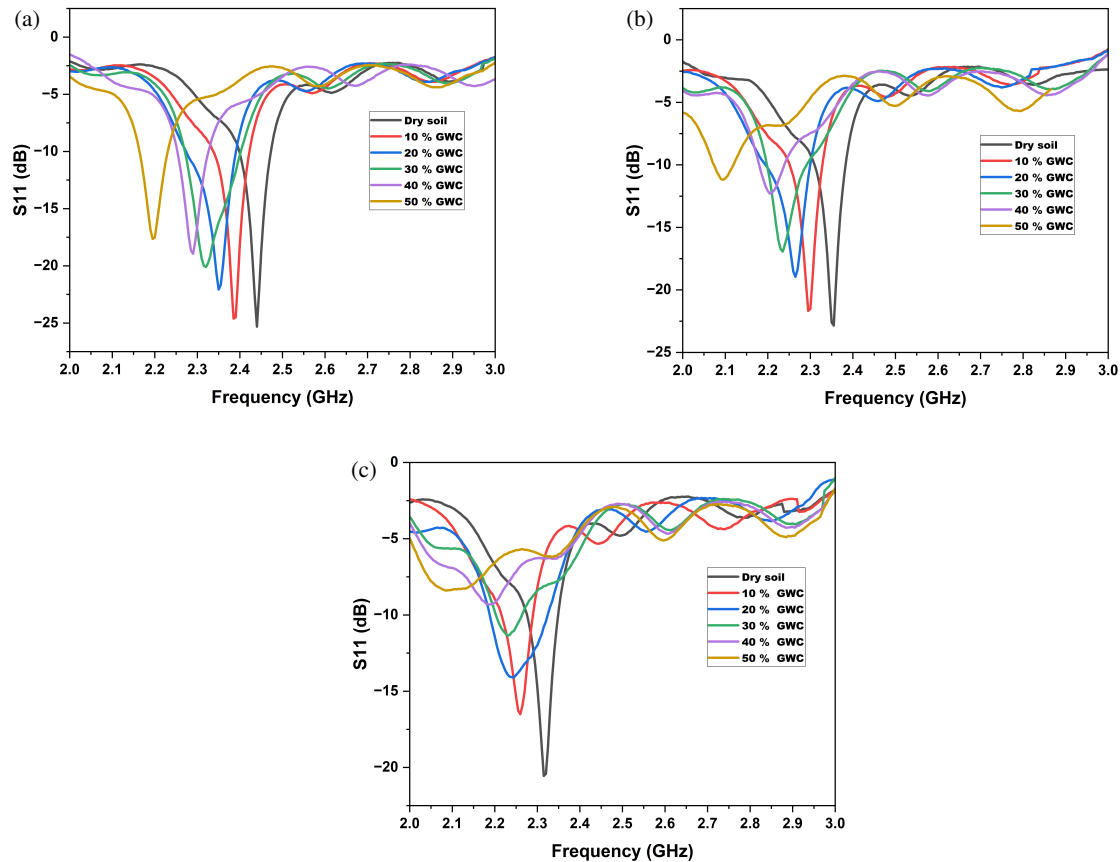


FIGURE 7. Measured S_{11} versus frequency of the proposed DMPA for varying GWC: (a) Sandy soil, (b) loamy soil, (c) clayey soil.

TABLE 4. Measured resonant frequency and reflection coefficient as a function of GWC for different soil samples.

| GWC (%) | Sandy Soil | | Loamy Soil | | Clayey Soil | |
|----------|-------------|---------------|-------------|---------------|-------------|---------------|
| | f_r (GHz) | S_{11} (dB) | f_r (GHz) | S_{11} (dB) | f_r (GHz) | S_{11} (dB) |
| Dry soil | 2.44 | -25.32 | 2.355 | -22.84 | 2.315 | -20.55 |
| 10 | 2.385 | -24.61 | 2.3 | -21.68 | 2.275 | -16.5 |
| 20 | 2.35 | -22.07 | 2.265 | -18.95 | 2.245 | -14.09 |
| 30 | 2.32 | -20.1 | 2.23 | -16.93 | 2.22 | -11.35 |
| 40 | 2.27 | -18.94 | 2.175 | -12.3 | 2.145 | -9.31 |
| 50 | 2.195 | -17.64 | 2.095 | -11.19 | 2.085 | -8.4 |

are in close agreement with the simulated data. The fabricated decagonal microstrip antenna resonates at 2.445 GHz with a measured S_{11} of -34.3 dB, closely matching the simulated value of -36.62 dB. The corresponding VSWR at resonance was measured to be 1.02, validating the excellent impedance match with the 50Ω feedline. The impedance measured at resonance is $50.47 + j0.074 \Omega$, which is nearly a match to the simulated value $49.32 + j0.17 \Omega$. The strong correlation between the simulated and measured results confirms the viability and performance of the decagonal microstrip antenna for the proposed soil moisture sensing application.

4.3. Soil Moisture Sensing Performance Analysis

The performance of the proposed decagonal microstrip antenna using a Taconic TLY-5 substrate as a soil moisture sensor across sandy, loamy, and clayey soils was experimentally validated by measuring its resonant frequency and S_{11} across varying gravimetric water contents (GWC). Figure 7 illustrates the variation in the resonant frequency and reflection coefficient with GWC across all three soil samples, and the corresponding values are summarized in Table 4.

As the soil moisture content increases, the effective dielectric constant of the soil increases, leading to a downward shift in the resonant frequency and a higher reflection coefficient owing to

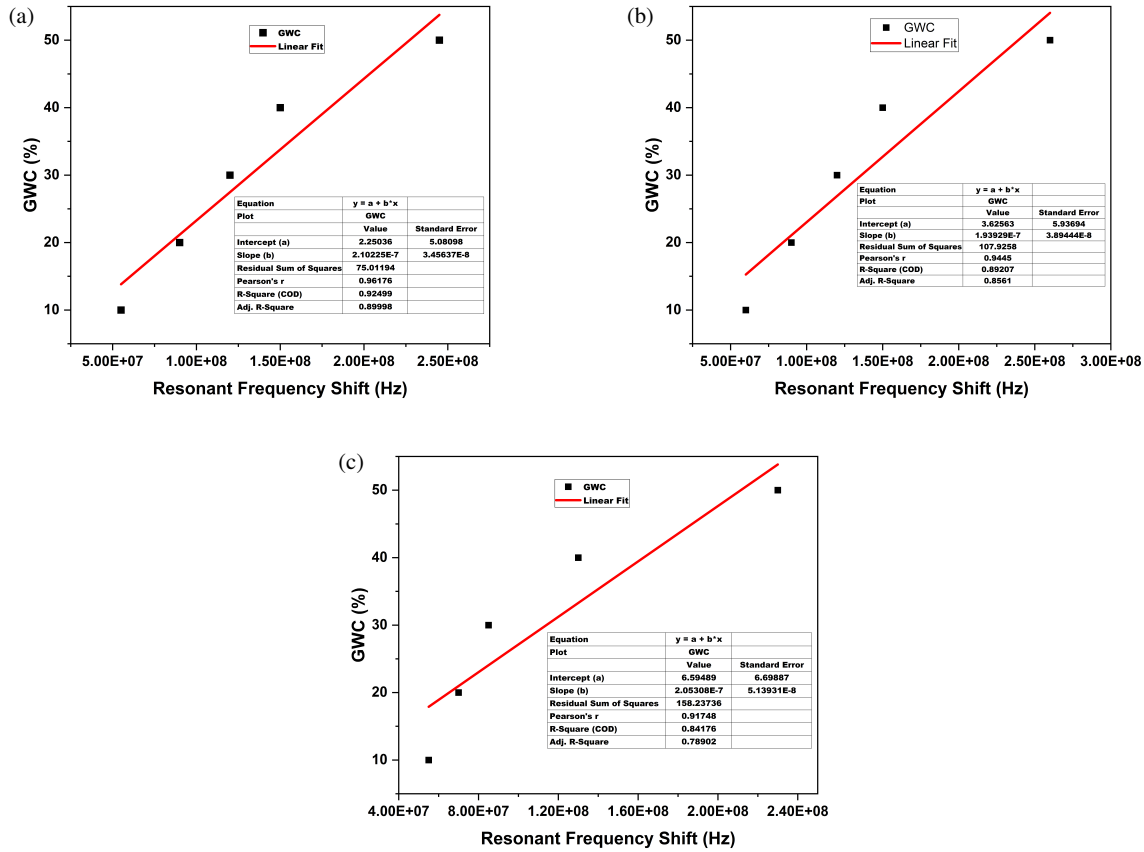


FIGURE 8. Regression analysis of resonant frequency shifts: (a) Sandy soil, (b) loamy soil, (c) clayey soil.

the increased impedance mismatch. This variation is due to the different mineral and bound water contents of the soils, which affects their initial and saturated dielectric properties. Linear regression analysis of resonant frequency shifts from sandy, loamy, and clayey soils was used to measure the soil moisture content, as illustrated in Figure 8. Regression analysis of the resonant frequency shifts was carried out using OriginPro 2024 software.

Regression analysis provided the following soil-specific equations, describing the linear relationship between the resonant frequency shift (Δf_r) in GHz and percentage moisture content (MC) [20]: Equation (5) for sandy soil with $R^2 = 0.925$, Equation (6) for loamy soil with $R^2 = 0.892$, and Equation (7) for clayey soil with $R^2 = 0.841$.

$$\%MC = 2.1 \times 10^{-7} \Delta f_r + 2.25 \quad (5)$$

$$\%MC = 1.94 \times 10^{-7} \Delta f_r + 3.63 \quad (6)$$

$$\%MC = 2.05 \times 10^{-7} \Delta f_r + 6.59 \quad (7)$$

The high coefficients of determination (R^2) for all three soil samples confirmed the strong correlation between the resonant frequency shift and soil moisture content. The resonant frequency shift was computed using Equation (8).

$$\Delta f_r = f_{r,dry\ soil} - f_{r,wet\ soil} \quad (8)$$

The gravimetric moisture content and percentage moisture content calculated from the measured resonant frequency shift

using soil-specific linear regression equations for the sandy, loamy, and clayey soil samples are summarized in Table 5.

The experimental results, summarized in Table 5, demonstrate the relationship between the antenna's measured resonant frequency shift and moisture content of each soil sample. Sandy soil, with its lower initial dielectric constant, exhibits the largest frequency shift, whereas clayey soil, owing to its higher mineral and bound water content, has a higher initial dielectric constant, resulting in a smaller overall frequency shift. Therefore, the proposed DMPA functions as a highly sensitive soil moisture sensor, effectively detecting variations in the surrounding medium.

The sensitivity (S) of the proposed soil moisture sensor was determined from the regression analysis of the experimental data presented in Figure 8 and is expressed by Equation (9), which is the inverse of the slope of the regression analysis curve. Table 6 summarizes the sensitivity values obtained for the three soil samples.

$$S = \frac{d(\Delta f_r)}{d(\%MC)} \quad (9)$$

The experimental validation demonstrated soil-specific sensitivity, with the resonant frequency shift yielding values of 4.76 MHz/% for sandy soil, 5.15 MHz/% for loamy soil, and 4.89 MHz/% for clay soil, confirming the proposed decagonal microstrip patch antenna's high-performance sensing capability across diverse agricultural environments.

TABLE 5. Moisture contents for different soil samples.

| GWC (%) | Sandy Soil | | Loamy Soil | | Clayey Soil | |
|---------|-----------------------|-----------|-----------------------|-----------|-----------------------|-----------|
| | Δf_r (GHz) | MC (%) | Δf_r (GHz) | MC (%) | Δf_r (GHz) | MC (%) |
| 10 | 0.055 | 13.8 | 0.06 | 15.27 | 0.055 | 17.865 |
| 20 | 0.09 | 21.15 | 0.09 | 21.09 | 0.07 | 20.94 |
| 30 | 0.12 | 27.45 | 0.12 | 26.91 | 0.085 | 24.015 |
| 40 | 0.15 | 33.75 | 0.15 | 32.73 | 0.13 | 33.24 |
| 50 | 0.245 | 53.7 | 0.26 | 54.07 | 0.23 | 53.74 |

TABLE 6. Sensitivity values for sandy, loamy, and clayey soil samples.

| Parameters | Sandy Soil | Loamy Soil | Clayey Soil |
|---------------------|----------------------|-----------------------|-----------------------|
| Slope | 2.1×10^{-7} | 1.94×10^{-7} | 2.05×10^{-7} |
| Sensitivity (MHz/%) | 4.76 | 5.15 | 4.89 |

5. CONCLUSION

This study demonstrates the design, fabrication, and performance of a novel compact high-gain decagonal microstrip patch antenna for real-time soil moisture sensing. Comparative analysis demonstrated the superiority of the Taconic TLY-5 substrate over FR-4, with the Taconic TLY-5 design achieving higher gain (7 dBi) and excellent radiation efficiency (96.5%). The reflection coefficient, resonant frequency, input impedance, and VSWR of the fabricated antenna closely matched the simulations, validating the design methodology. The soil moisture sensing capability of the proposed antenna is validated by consistent shifts in the resonant frequency and reflection coefficient with varying gravimetric water content (GWC). Linear regression analysis was performed on the experimental data from sandy, loamy, and clayey soils, yielding a high coefficient of determination ($R^2 \approx 0.9$) for all three soil types. This analysis enabled the conversion of the measured frequency shift into percentage moisture content, demonstrating the potential of the antenna as a high-performing, nondestructive soil moisture sensor. The compact size, high gain, and predictable strong sensing capability, achieving soil-dependent sensitivities up to 5.15 MHz/%, make the proposed DMPA a better choice for integration into wireless sensor networks for smart agriculture and environmental monitoring.

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