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Measurement of Soil Moisture Using Microwave Sensors Based on BSF coupled lines †

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Abstract: This research introduces the conceptualization and examination of a microwave sensor incorporated with a microstrip band stop filter. The microwave sensor's design and assessment are based on microstrip parallel coupled lines, employing a band stop filter configuration at 2.45 GHz on FR4 substrate. The study encompasses the evaluation of soil moisture spanning from 20 to 80%. The measurement procedure involves a network analyzer, specifically the KEYSIGHT model E5063A, operating within the frequency range of 100 kHz to 4.5 GHz. The investigation centers on scrutinizing the frequency response of the insertion loss (S_{21}) across this spectrum. The outcomes of the experimentation unveil notable disparities in frequency shifts. The resultant frequency values, labeled as (f_0-f_1), manifest at 0, 18, 60, 89, 145, and 200 MHz, sequentially. Remarkably, the correlation between the percentage representation of the frequency shift in the transmission coefficient and the frequency itself emerges distinctly, even as the range of tested samples is fine-tuned.

Keywords: Soil Moisture; Microwave Sensors; BSF coupled lines

1. Introduction

Recent advancements in wireless and mobile communication technologies, driven by the escalating demand for higher transmission rates and lower latency, have ignited widespread interest among researchers [1]. They are actively working on developing sensors capable of collecting data on the electromagnetic characteristics of dielectric materials within the communication channel and monitoring soil moisture levels [2]. These sensors play a crucial role in applications related to both communication and agriculture, ensuring efficient communication channels and improved crop management. Furthermore, the ability to measure soil properties, such as moisture content, provides invaluable benefits for agriculture. Accurate soil moisture data enables farmers to make informed irrigation decisions, leading to optimal water usage and healthier crops. This technology also aids in preventing overwatering or underwatering, minimizing the risk of crop yield reduction and water wastage. By integrating communication technology with soil property measurement, these advancements showcase their potential to revolutionize how we communicate and how we cultivate the land and manage our vital resources.

Using microwaves to measure material properties involves employing microwave waves for material inspection and analysis. It finds applications in:

Dielectric properties: measuring electrical characteristics and microwave signal transmission by passing waves through materials. Moisture measurement: detecting moisture changes in materials through microwave wave frequency shifts. Distance

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measurement: gauging distances by measuring wave travel time between a transmitter and receiver. Material thickness: measuring material thickness based on wave penetration and reflection. This technique has broad applications, including material testing, food moisture assessment, microwave temperature control, and more.

In paper [1], presents a compact sensor utilizing the complementary split-ring resonator (CSRR) structure to assess relative permittivity in various dielectric materials and determine soil water content (SWC). The sensor consists of a circular microstrip patch antenna supporting a 3D-printed cylindrical container made from ABS filament. The operational principle relies on changes in two antenna resonant frequencies due to variations in the relative permittivity of the material under test (MUT). Simulations inform the development of an empirical model, and the sensor's sensitivity is examined through the characterization of typical dielectric materials. The sensor is versatile and applied to estimate water content in different soil types. Prototypes are fabricated and compared with other research to validate effectiveness. Additionally, the sensor accurately determines water concentration in quartz sand and red clay samples.

In paper [3], developed a compact microwave sensor using a circular microstrip patch antenna with two slotted complementary split-ring resonators (CSRRs). This sensor accurately characterizes the relative permittivity of different dielectric materials and measures water concentrations in various soil types. Its operating principle relies on comparing resonant frequencies with and without Material Under Test (MUT). Our sensor exhibits high sensitivity, requires minimal MUT samples, and is cost-effective, lightweight, and easy to produce. We also established an empirical model linking resonant frequency to MUT permittivity, demonstrating strong results for known materials. The sensor's versatility extends to medical, agricultural, and chemical applications due to its sensitivity, low profile, compact size, and planar design.

In paper [4], passive microwave sensors estimate soil moisture using brightness temperatures at low microwave frequencies, with vegetation optical depth as a key factor. Retrieval algorithms aim to concurrently determine vegetation optical depth (VOD) and soil moisture (SM). However, these algorithms, often based on τ-ω models, which consist of two third-order polynomial equations, can yield multiple solutions due to structural uncertainty. That this structural uncertainty significantly affects VOD and SM retrievals, emphasizing the need to address it in soil moisture estimation algorithms.

In paper [5], presents machine learning models for accurate soil moisture estimation using a short-range radar sensor operating at 3–10 GHz. The sensor measures volumetric water content by analyzing reflected signals. Input features extracted from these signals train various machine learning models, including neural networks, support vector machines, linear regression, and k-nearest neighbors. Model performance is assessed using metrics like root mean square error (RMSE), coefficient of determination (R2), and mean absolute error (MAE). Among the models, neural networks achieve the best performance with an R2 value of 0.9894. The research aims to offer cost-effective solutions, particularly for agriculturists, to enhance soil moisture monitoring accuracy.

In paper [6] presents a corrosion-resistant, embeddable open-end coaxial cable soil moisture sensor. It utilizes a microwave resonator with two key components along the coaxial line: a metal post at the signal input end and a metal plate parallel to the open end, separated by a moisture-sensitive polyvinyl alcohol (PVA) film. The sensor's resonance frequency is highly sensitive to fringe capacitance, which varies with soil moisture levels. Monitoring these frequency changes allows precise tracking of soil moisture fluctuations. The article includes a detailed mathematical model for the embeddable open-end microwave coaxial cable resonator (EOE-MCCR) and demonstrates its effectiveness in soil moisture measurement. In experiments covering soil moisture levels from 4% to 24%, the prototype sensor exhibits impressive sensitivity: 0.76 MHz/% for soil moisture between 4% and 10% and 1.44 MHz/% for soil moisture between 10% and 24%. This sensor is durable, cost-effective, corrosion-resistant, and suitable for long-term and potential industrial applications.

In paper [7], focuses on soil moisture sensors for long-term monitoring of moisture levels in highway subgrades and similar applications. Two microwave sensor designs, operating in the 4 to 6 GHz range, were studied. The first design uses a low-loss dielectric slab waveguide with a relative dielectric constant of 25. It provides high-resolution measurements for finely divided soils like bentonite clay, covering moisture levels from 10 to 50 percent by dry weight within effective sample volumes of 20 to 40 cm^2. A model based on the index of refraction offers effective dielectric constant values that reasonably match experimental results when considering ionic conduction effects. The second sensor design is better suited for coarser materials like crushed limestone aggregate. It launches waves from a tapered dielectric slab and can handle aggregate particles passing through a 0.63 cm mesh sieve. It offers satisfactory resolution for moisture levels ranging from 0 to 10 percent by dry weight. These sensor designs have the potential for effective and long-term soil moisture monitoring in various applications, including highway subgrades.

Finally, in paper [8] conducted observations using a dual-frequency radiometer (operating at 1.4 and 2.65 GHz) over both bare soil and corn fields for extended periods in 1994. When comparing emissivity and volumetric soil moisture at four different depths for bare soils, we found a clear correlation between the 1 cm soil moisture and the 2.65-GHz emissivity, as well as between the 3-5 cm soil moisture and the 1.4 GHz emissivity. These findings validate previous research. Our observations during drying and rainfall events reveal that these data provide valuable and novel insights for hydrologic and energy balance studies. Recent advancements in wireless and mobile communication technologies have led researchers to develop various sensors for measuring soil moisture and dielectric properties. While existing methods have made significant contributions to the field, they often face limitations in terms of accuracy, cost-effectiveness, and ease of implementation. In this context, our research introduces a novel microwave sensor design incorporating a microstrip band stop filter, aimed at addressing the shortcomings of traditional methods. By utilizing microstrip parallel coupled lines with a band stop filter configuration at 2.45 GHz on FR4 substrate, our approach offers improved precision in measuring soil moisture. This paper aims to present the benefits and unique characteristics of our proposed sensor, highlighting its advantages over existing techniques. This paper presents the design and analysis of a microwave sensor for the measurement of soil moisture using an FR4 substrate and microstrip parallel coupled lines, as illustrated in Fig. 1. The measurements were conducted using the KEYSIGHT model E5063A network analyzer. The paper is structured as follows: Section II covers the design and analysis of the computational band-stop filter based on microstrip parallel coupled lines. Section III outlines the experimental setup and methodology. Section IV presents the results and discusses their implications. Finally, Section V provides the conclusion.

Figure 1. The band stop filter based on microstrip parallel coupled lines for microwave sensor.

2. Methods

2.1. Design and Analysis

The design proposes a structure consisting of microstrip parallel coupled lines. The signal transmission lines are designed using a dielectric substrate with a constant dielectric permittivity, while the upper sides of both signal transmission lines are made of air with constant dielectric permittivity. Additionally, a plastic frame has been created to house the experimental samples. The proposed design involves a structure comprising microstrip parallel coupled lines with strip transmission lines. These signal transmission lines are implemented on a dielectric substrate with a constant dielectric permittivity. The upper sides of both signal transmission lines maintain a constant dielectric permittivity, being in contact with air. Below the dielectric substrate, a metal plane serves as the ground plane. Typically, the length of the parallel-coupled microstrip lines is approximately equal to the wavelength of the transmission lines. This occurs because these lines are situated on an inhomogeneous medium, leading to certain effects when these transmission lines are utilized in circuits or devices operating in the microwave frequency range. The characteristic impedance of both even and odd modes (Z_{0e}, Z_{0o}) can be expressed through simple equations, as depicted in Equations (1) and (2) respectively.

$$Z_{0e} = Z_0\sqrt{\frac{1-C}{1+C}}, \tag{1}$$

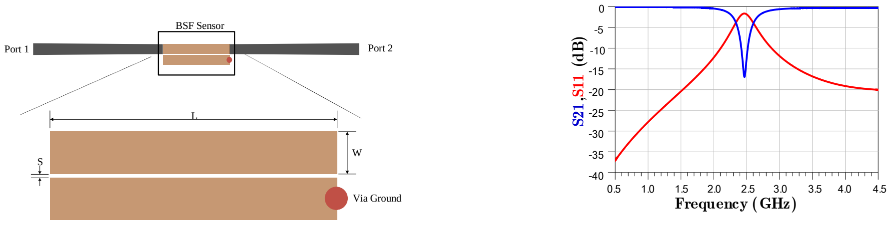
$$Z_{0o} = Z_0\sqrt{\frac{1+C}{1-C}} \tag{2}$$

The characteristic impedance for even and odd modes, denoted as Z_{0e} and Z_{0o} respectively, can be described by simple equations as shown in Equations (1) and (2) base on $Z_0 = \sqrt{Z_{0e}Z_{0o}}$. In Fig. 1, the microwave sensor, based on microstrip parallel coupled lines, is employed for assessing the characteristics of various solutions and their electrical properties within the microwave frequency range. We take into account the parametric impedance equations [9] that define a circuit representing a microwave sensor with parallel coupled lines [9]. Replace the impedance parameters with the given values to determine the S-parameters of a 2-port network where S_{11} represents the return loss (dB), and S_{21} represents the insertion loss (dB).

$$S_{11} = \frac{Z_{11T}^2 - Z_0^2 \quad - Z_{12T}Z_{21T}}{Z_{11T} + Z_0 \quad Z_{22T} + Z_0 \quad - Z_{12T}Z_{21T}} \tag{3}$$

$$S_{21} = \frac{2Z_0Z_{21T}}{Z_{11T} + Z_0 \quad ^2 - Z_{12T}Z_{21T}} \tag{4}$$

Figure 2(a) the physical dimension of proposed and Figure 2 (b) depicts the simulated outcomes of the proposed band-stop filter, presenting the S_{11} and S_{21} S-parameters. The frequency response simulations span from 500 MHz to 4.5 GHz, based on laboratory measurements utilizing available equipment. A comparison is drawn between the ideal simulation and the practical implementation of the microstrip under real operating conditions. In these simulation results, S_{11} represents the return loss, indicating the reflection coefficient, while S_{21} represents the insertion loss, indicating the transmission coefficient. It illustrates the power transmission from port 1 to port 4, denoted by S_{21}, with the same interpretation. Notably, there is an enhanced power performance at 2.45 GHz and subsequent frequencies in the ideal scenario. The physical structure of the prototype corresponds to a microwave microstrip line sensor.



(a) (b)

Figure 2. The simulated outcomes of the suggested band-stop filter [3].

This paper aims to design and analyze a microwave sensor for soil moisture measurement, utilizing an FR4 substrate with microstrip parallel coupled lines, as depicted in Figure 1. The measurements were carried out using the KEYSIGHT model E5063A network analyzer. We are currently in the process of developing a sensor that employs microstrip parallel coupled lines, operating at a frequency of 2.45 GHz, and constructed with FR4 material. Concurrently, we are building a prototype for soil moisture measurement. It is crucial to consider the following key parameters: a relative dielectric constant (ε_r) of 4.55, a base material height (h) of 1.6 mm, and a loss tangent (tan δ) of 0.02, as shown in Figure 3. These parameter values are crucial for determining the dimensions of the microstrip transmission line required to achieve our desired frequency. Our design encompasses a microstrip band-stop filter characterized by a width of 2.45 mm, a spacing (S) of 0.2 mm, and a length of 17.06 mm. Within this length, there is a designated region for conducting measurements. Furthermore, we have integrated an SMA connector into the sensor structure using a parallel microstrip configuration operating at 2.45 GHz. The physical structure of our prototype is characterized by a width (W) of 2.45 mm, a spacing (S) of 0.2 mm, and a length (L) of 17.06 mm as in Figure 3.

2.2. The samples of soil moisture levels

In the experimental setup involving various soil moisture measurement methods, the test samples employed in this experiment have undergone a production process to determine soil moisture content. For the samples of interest, soil moisture intensity was assessed using a common method involving a soil moisture meter. The device utilized is depicted in Figure 4(a). Furthermore, distinct soil moisture meter values can be derived from this relationship, enabling the measurement of soil moisture content expressed in volume or % SMBV (Soil Moisture by Volume). In this research, soil moisture intensity measurements are presented on a scale ranging from 0% to 100% in 20% increments, corresponding to different Soil Moisture concentrations. The mixtures are prepared by commencing with a specific soil moisture level and subsequently adding distilled water in proportionate amounts using concentration equipment, as shown in Figure 4 (b). The frequency response of S_{21} was measured using the KEYSIGHT model E5063A (ENA Series Network Analyzer), which operates in the frequency range of 100 MHz to 4.5 GHz, employing the proposed the BSF based on the microstrip parallel coupled line sensor prototype.

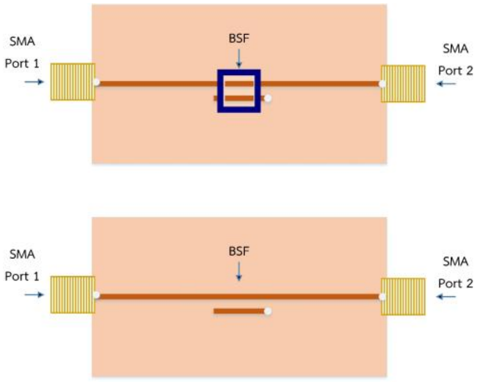
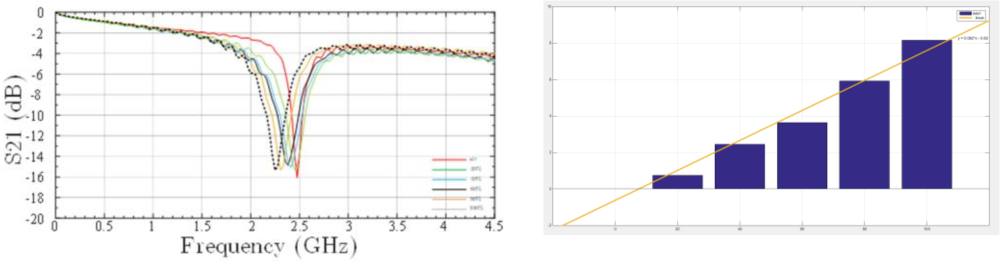


Figure 3. The prototype band stop filter for measurement of soil.

(a) (b)

Figure 4. The experimental setup involves various methods for measuring soil moisture.



(a) (b)

Figure 5. The measurement results (a) of insertion loss (S_{21}) at different soil moisture levels, (b) the relationship of the frequency shifted.

3. Result and Discussion

The results of the microwave sensor measurement with the microstrip BSF prototype were obtained using the KEYSIGHT brand E5063A (ENA Series Network Analyzer) within the frequency range of 100 MHz to 4.5 GHz. In Figure 5 (a), the results of the insertion loss (S_{21}) experiment were measured on samples tested at different soil moisture levels, including 0% (air), 20%, 40%, 60%, 80%, and 100%. The measurement result for the insertion loss (S_{21}) efficiency with air at a frequency operation of 2.45 GHz is -15.12 dB, the soil moisture 20% is -14.92 at 2.432 GHz, the soil moisture 40% is -14.85 at 2.390 GHz, the soil moisture 60% is -15.01 at 2.361 GHz, the soil moisture 80% is -15.02 at 2.305 GHz, and the soil moisture 100% is -15.01 at 2.250 GHz. The frequency decreases accordingly as 0 MHz, 18 MHz, 60 MHz, 89 MHz, 145 MHz, and 200 MHz. The percentage change refers to the relative difference between two values, expressed as a percentage. It is often used to measure the increase or decrease in quantity over time or between two different states—the formula to calculate the percentage change as in Figure 5 (b) shows the analysis of the correlation of soil moisture with the frequency shifted according to the soil moisture from 0-100%, respectively. The percentage difference was 0.00, 0.735, 2.449, 3.633, 5.918, and 8.163 % between frequency increases with the soil moisture level. The experimental results show a linear relationship between the soil moisture level and by BSF microstrip sensor.

4. Conclusion

In conclusion, our study demonstrates the efficacy of the microwave sensor design based on microstrip parallel coupled lines with a band stop filter for accurate soil moisture measurement. The experimental results consistently show a strong correlation between the frequency shifts and varying soil moisture levels, underscoring the reliability and precision of our proposed approach. Compared to traditional methods, our sensor offers distinct advantages in terms of cost-effectiveness, accuracy, and ease of implementation, making it a valuable tool for agricultural and environmental applications. As our research contributes to the ongoing advancements in soil moisture measurement technology, future studies could focus on integrating this approach into broader environmental monitoring systems and precision agriculture practices.

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