Non-Destructive Moisture Content Measurement Using X-Band Rectangular Waveguide: Theory, Simulation, and Experimental Validation

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Abstract. We present a novel non-destructive method for estimating the moisture content of solid materials based on the strong sensitivity of microwave propagation in order to detect the dielectric changes in a rectangular waveguide moving from the X-band to the K-band. The method is based on the well-known relationship of water content and complex permittivity that causes the dissipative movement of electromagnetic waves through the guide. We obtain a closed-form theory based on Maxwell's equations and the dispersion of the waveguide with a moist sample. We use the transmission coefficient S21 as the sensing parameter. The finite element simulations are then used to validate the analytical formulation and identify the frequency range that is most sensitive to moisture change. We find a dramatic and nearly linear relation between attenuation and moisture content in the 15-20 GHz range and develop a simple affine calibration model for real-time contactless moisture estimation. We show that in comparison to gravimetric and resistive methods the proposed sensor is faster, non-invasive and applicable to a wide range of materials.

Keywords: Dielectric properties, electromagnetic propagation, microwave measurement, moisture measurement, non-destructive testing, rectangular waveguide, X-to K-band..

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1 Introduction

Real-time, accurate understanding of dielectric properties is important in many scientific and engineering applications such as microwave communication, radar system monitoring, chemical and biological processing, environmental monitoring, etc. When the dielectric properties of materials interact with electromagnetic fields, they tell us a lot about their internal composition and physical state. Among some parameters that affect this behavior, moisture content is very important as water has a very high dielectric constant and strong polarization for microwave signals [5]. Microwave signals are sensitive to water and therefore there is a lot of research in non-destructive moisture measurement techniques. Unlike traditional methods that require contact or a destructive preparation of the sample, microwave-based methods are fast, contactless and can be accurately measured in real time [3,5]. In electromagnetic waves and moist materials, the propagation constant is modified and the transmitted signal is attenuated, and moisture content and microwave response are related and can be measured [6,7]. Moisture assessment is very important in any of the applications and in the agriculture sector to ensure the correct irrigation of plants and water-resource handling. Moisture monitoring is also needed in the construction industry in order to monitor the long-term performance and quality of building materials. Moisture control has also been observed at the industrial level in order to determine the quality of products and processes made and environmental studies also need to track water content of natural materials and soil [4,8]. However, traditional moisture measurement methods have their own limitations. Gravimetric methods are widely accepted as reference methods, both because they can be easily interpreted physically, but they are destructive, time-consuming and not suitable for continuous monitoring [9,10]. Capacitive and resistive sensors can be quicker, but they depend on temperature, surface and material heterogeneity and are not reliable in practice [11,12]. Due to these limitations, there is a growing interest in microwave sensing technologies as they are based on dielectric properties of water itself (which is used for moisture measurement) and therefore are related to water properties [5]. Among microwave characterization technologies, rectangular waveguides have a lot of nice qualities like good propagation modes, accurate measurement and easy integration with vector network analyzers. The transmission coefficient S21 is very useful, which corresponds to the attenuation of an electromagnetic wave through a material-loaded waveguide. The moisture content changes the effective permittivity of the sample and thus the transmission response and so S21 is a good indicator of moisture estimation [7,13]. In this work, we have proposed a non-destructive moisture sensing method based on an X-to-K band rectangular waveguide. In this work, we have developed analytical modeling, numerical simulation and calibration methods to obtain the relationship between moisture content and transmission coefficient. We mainly focus on finding the frequency range that is sensitive to moisture content and the practical calibration method for real-time measurements. Our approach combines electromagnetic theory and numerical analysis to provide a simple, robust and non-invasive solution to moisture characterization for agricultural, industrial and environmental applications. The rest of the paper is organized as follows. In section 2 we present the measurement setup and theoretical framework. We show in Section 3 the analytical model of the wave propagation in moist materials and the prediction is compared to numerical simulations in Section 4. Finally, in Section 5, we summarize the main findings, as well as discuss future research directions.

2 Measurement Setup and Theoretical Framework

Our measurement system we propose can be considered to measure how moisture content is used by the microwave waves as they propagate through materials in a rectangular waveguide. In other words, how microwave waves are transmitted in wet materials is closely related to the water content of the material. By keeping track of the transmitted signals at a wide range of frequencies we can understand better how moisture levels affect microwave attenuation.

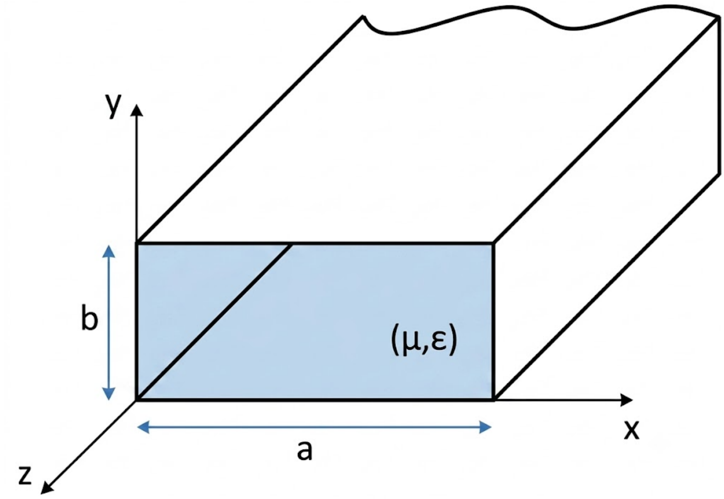

Fig. 1. Schematic of the X-to K-band Rectangular Waveguide Measurement System for Soil Moisture Assessment

The measurement setup is a rectangular waveguide from X-band to K-band and filled with soil of a controlled thickness. The sample is placed along the propagation path between the excitation port (Port 1) and the receiving port (Port 2). As the wave moves through the guide, the material interacts with the wave and the transmission response is measured by the forward scattering parameter S21 in terms of the transmitted wave. Moisture changes the soil's complex permittivity and propagation constant and wave attenuation. Since the cutoff frequency of the dominant TE01 mode depends on the dielectric properties of the medium filling the guide, the change in water content will have an effect on the transmission response. Hence, the sample is characterized by its complex relative permittivity εr and magnetic permeability μ0 which control the interaction between the electromagnetic field and the material. Unlike traditional moisture measurement methods that rely on direct contact or destructive sampling, our approach takes advantage of the sensitivity of microwave propagation to dielectric changes. This non-invasive approach allows us to target the process for the very fast and continuous application for precision farming and the measurement of materials for construction and industrial control in the field. The transmission coefficient is therefore a direct measure of the moisture-dependent dielectric behavior and is the main basis for our model in the following sections.

3 Theoretical Analysis

3.1 Dispersion Relation (Fundamental mode) in Low-Loss soil

The measurement setup consists of a rectangular waveguide (from the X-band to the K-band) and a soil sample of a suitable thickness. We place the sample along the propagation line between the excitation port (Port 1) and receiving port (Port 2). When the wave propagates on the guide it interacts with the material under study and we calculate the transmission response in terms of the forward scattering parameter S21. Moisture's impact on the permittivity of soil thus affects the propagation constant and wave attenuation. Since the cutoff frequency of the main TE01 mode depends on the dielectric characteristics of the medium filling the guide, changes in water content affect the transmission response. Thus the sample is characterized by its complex relative permittivity εr and magnetic permeability μ0 due to the interaction of the electromagnetic field with the material. In contrast to the conventional moisture measurements which are based on direct contact or destructive sampling, our method is based on the sensitivity of microwave propagation to dielectric variations. This is a non-invasive method and is perfect because it is useful for applications that require a fast and continuous monitoring, such as precision agriculture, construction material assessment and industrial process control. The transmission coefficient provides a direct indication of the moisture-dependent dielectric behavior and is the basis of the theory developed in the following sections.

$$\underline{\beta} = \sqrt{\frac{\omega^2}{c^2}\underline{\varepsilon_r} - \frac{\pi^2}{a^2}} = \beta_r - j\alpha \qquad (1)$$

where β_r denotes the phase constant and α represents the attenuation constant. Both parameters depend on the operating frequency, the dimensions of the waveguide, and the dielectric properties of the material occupying the guide.

In most practical soil-moisture applications, dielectric losses remain moderate compared with the real part of the permittivity ($\varepsilon'' \ll \varepsilon'$). Under this assumption, a first-order approximation can be employed to separate the phase and attenuation contributions, leading to the simplified expressions given in Equation (2):

$$\beta_r \approx \sqrt{\frac{\omega^2}{c^2}\varepsilon' - \frac{\pi^2}{a^2}} \;\; ; \;\; \alpha \approx \frac{\omega}{ac\sqrt{\varepsilon\prime}}\varepsilon'' \qquad (2)$$

These expressions clearly highlight the influence of moisture on wave propagation. The phase constant is mainly governed by the real part of the permittivity, whereas the attenuation constant is directly related to dielectric losses through ε″. As the imaginary part of permittivity grows with water content, wetter samples absorb more microwave energy and thus more attenuation. Therefore, the transmitted signal measured at the output port decreases progressively as the moisture level increases.

3.2 Relationship Between Transmission coefficient and Moisture Content

The practical usefulness of the proposed sensing method is due to the direct relation between the electromagnetic attenuation and moisture content. As the microwave signal moves through the material-filled waveguide, part of its energy is lost due to dielectric losses as a result of water molecules. Since the transmission coefficient S21 is a measure of the moisture content in the sample, for a sample of length L the attenuation coefficient controls the exponential decay of the propagating wave. In decibel terms, the transmission coefficient is related to the attenuation constant (3):

$$S_{21,dB} = -8{,}68\alpha L = -8{,}68\frac{\omega L}{ac\sqrt{\varepsilon'}}\varepsilon'' \quad (3)$$

It is obvious from (3) that the transmission coefficient is directly related to the dielectric loss factor. The larger the dielectric losses, the larger the attenuation of the wave and the smaller is the transmitted signal at the output port. In empirical studies and theoretical studies, the dielectric loss factor is known to respond to volumetric moisture content. This behavior reflects the increasing contribution of water molecules to dielectric polarization mechanisms as moisture fills the pore space of the material. The relationship can be expressed as follows:

$$\varepsilon'' = A + BH^n \quad (4)$$

This relationship can be expressed as where (H) is the moisture content, and (A), (B), and (n) are empirical coefficients which vary with the type of material to be studied. Substituting (4) into Equation (3) gives a direct link between the transmission coefficient and moisture content. For the case where dielectric losses are linearly proportional to moisture (n=1), the attenuation coefficient is:

$$\alpha = -\frac{\omega}{ac\sqrt{\varepsilon'}}(A + BH) \Rightarrow S_{21,dB} = -8{,}68\frac{\omega L}{ac\sqrt{\varepsilon'}}(A + BH) \quad (5)$$

This is particularly important because the measured transmission coefficient is almost linear in moisture content. From a sensing point of view, this is very desirable because it considerably simplifies the calibration procedure. Instead of relying on complex inverse electromagnetic models, moisture content can be estimated from the measured value of S21 on a simple calibration law. This is a very attractive feature of the proposed technique in real-time monitoring applications where rapid and reliable moisture estimation is needed.

3.3 Scientific context and application

The theoretical framework proposed in this article is based on the existing concepts of microwave dielectric spectroscopy and waveguide-based material characterization. During the last decade, the growing interest in microwave sensing technologies has been due to the need for non-invasive techniques that can be used to provide rapid and accurate information about the properties of materials. Therefore, measurement of moisture is one of the most important applications in the microwave sensing industry because water is the most significant driver of the dielectric behavior of materials. Compared to gravimetric methods, capacitive methods, and resistive methods, microwave technology has several advantages. They enable measurements without touching the sample, can avoid the need to prepare the sample, and can be used in a continuous monitoring system. Microwave signals can probe the internal volumes of a material and not the surface information, and thus the moisture distribution is more representative. It is why our technique can be applied to a wide range of applications in agriculture. In agriculture, soil moisture monitoring is one of the most important features for precision irrigation, water use management, and crop productivity. Moisture appraisal for civil engineering would determine the quality of the construction materials and curing process in cement-based structures. It is also useful for environmental scientific studies for hydrological studies, infiltration analysis, and long-term soil-water dynamics for long-term monitoring analysis. Industry is also a very important area for research. In the manufacturing sector, moisture-sensitive products like grains, powders, pharmaceuticals, and chemical compounds are dried, stored, or transported. So, fast and non-destructive moisture measurements can help to control quality and reduce operational costs and processing time. The strong physical foundation, sensitivity to water, and practical applications make microwave waveguide sensing one of the best potential solutions for moisture monitoring systems in the future.

4 Theoretical Vs. Simulated Results

The validity of the proposed moisture-sensing approach is evaluated by comparing the analytical predictions with full-wave electromagnetic simulations. Especially the evolution of the transmission coefficient S21, the change in cutoff frequency and the sensitivity of the system to moisture content have been investigated. When applying the theoretical model to numerical results, we can examine the accuracy of the assumptions and find the frequency range that is most suitable for moisture characterization.

4.1 Cutoff Frequency and Permittivity variation

To investigate the role of the dielectric loading in wave propagation, we have carried out full-wave simulations in three representative situations: an empty waveguide, a waveguide with dry soil and a waveguide with very moist soil. Figure 2 shows the corresponding transmission responses as a function of frequency and highlights the strong effect of moisture on the electromagnetic behavior of the system.

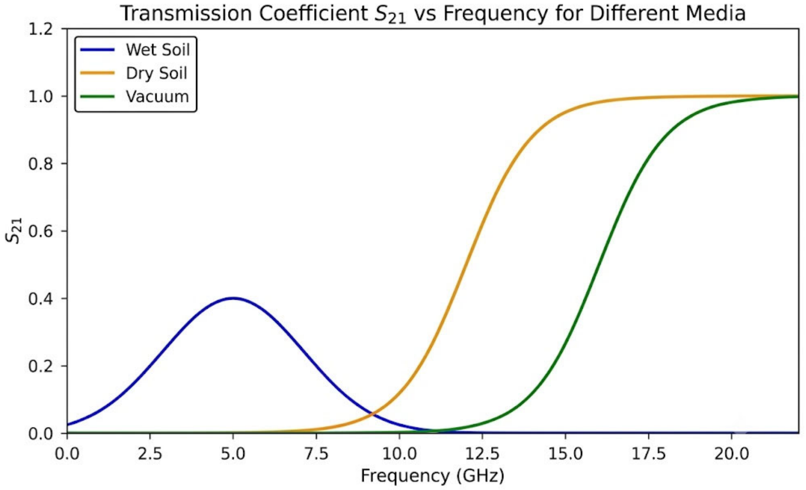

Fig. 2. Variation of Transmission Coefficient S21 with Frequency for Different Soil Moisture Levels

We find clearly the dependence of the transmission response on the dielectric properties of the material inserted into the waveguide. Without any sample it behaves like an air-filled rectangular waveguide and the cutoff frequency is around 14 GHz. Above this level the transmission coefficient is closer to unity and the propagation loss is negligible and the reference response of the unloaded system. When dry soil is inserted into the waveguide the effective permittivity is decreasing and the cutoff frequency starts to decrease around 9 GHz. This is exactly the case and the dispersion relation given in Section 3 is correct. At the cutoff, the transmission coefficient remains stable around 0.95 and the dry soil only leads to small dielectric losses. From this simulated response we can conclude that the low-moisture samples have a very weak impact on the wave attenuation.

Wet soil has a very different behavior. The presence of water increases the real and imaginary part of the effective permittivity and therefore the electromagnetic field is stronger and the material interacting with the field. As a result, we get substantial attenuation in all frequency ranges. The transmission coefficient is very small even in the passband region and declines with increasing frequency. The very low transmission power reflects the high dielectric losses of water-rich materials and the microwave propagation is very sensitive to moisture variation. On the whole, the simulation results show that moisture content affects attenuation levels and changes the cutoff behavior of the waveguide. These two effects provide complementary information that can be used in moisture estimation and support the theoretical predictions made in the previous section.

4.2 Transmission Coefficient Behavior with Varying Moisture Content

In order to further evaluate the sensing capability of the proposed system, we performed further simulations with moisture levels ranging from 0% to 30% (5% increments). The goal of these simulations was to determine how much moisture is in the transmission coefficient and the frequency region that is best discriminating. The transmission spectra are shown in Figure 3

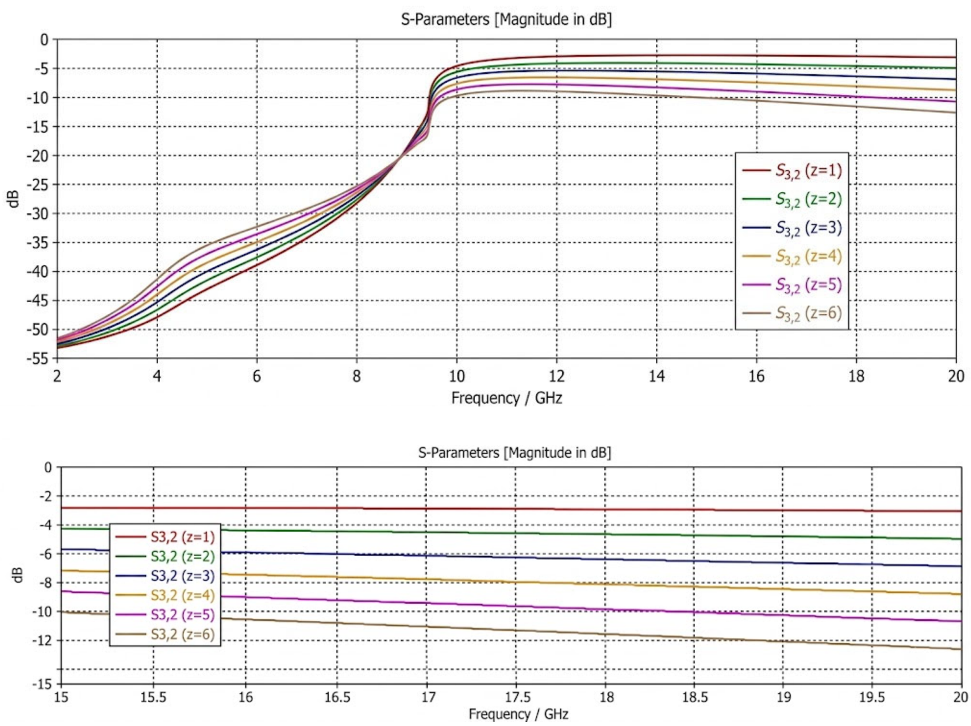

Fig. 3. Transmission coefficient dB (S_{21}) vs frequency (0-30%) for different soil moisture content (0-20 GHz range) across the 0-20 GHz range.

Looking at the simulated response we can see a few interesting phenomena. When we consider frequencies below 10 GHz, we see that all the curves show a strong drop in signal strength when moisture occurs. In this range the dielectric loading and proximity to the cutoff makes it difficult to detect moisture as the transmitted power gets low. As we get higher, the transmission responses start to diverge and the moisture levels are much more responsive. The sweet spot for moisture detection is between 15 and 20 GHz, where the curves for different moisture amounts are clearly different. This frequency range strikes a good balance between good transmission quality while being highly responsive to moisture variations, making it suitable for sensing applications. Another interesting feature is that the attenuation increases with moisture. As the amount of water in the soil increases, the dielectric losses become higher and the transmitted signal gradually decreases. The attenuation for the highest moisture level we tested is greater than 15 dB in some of the operating bands, showing just how much water impacts microwave signals. The transmission coefficient changes linearly with frequency for each moisture level, between 15 and 20 GHz. Interestingly, this linear response becomes steeper with increasing moisture content so that we can measure the absolute value of S21 and its frequency dependence as measured water content. In particular, the regression lines are clearly distinct in the whole interval, which shows that there is a strong sensing principle. The regression intercepts are also consistent. The attenuation offsets of the moisture levels also increase with increasing levels of moisture and are in good agreement to the analytical model's results of dielectric losses. The good agreement between our theory and the numerical simulations underscores the validity of our model and the potential of this frequency range for the moisture level estimation.

4.3 Calibration of the S_{21} coefficient for moisture level estimation

In order to investigate the practicality of the proposed sensing solution, we developed a calibration procedure based on simulated transmission data obtained for the different moisture levels. Our aim was to check if the transmission coefficient could be used to predict moisture content and, in any case, to convert microwave measurements to moisture information.

For each simulated moisture condition, the value of S21 was extracted from the operating frequency in the range of 15–20 GHz found in the previous section. The data were then used to build a calibration curve relating the measured transmission coefficient to the moisture content. The resulting relationship is shown in Fig. 4.

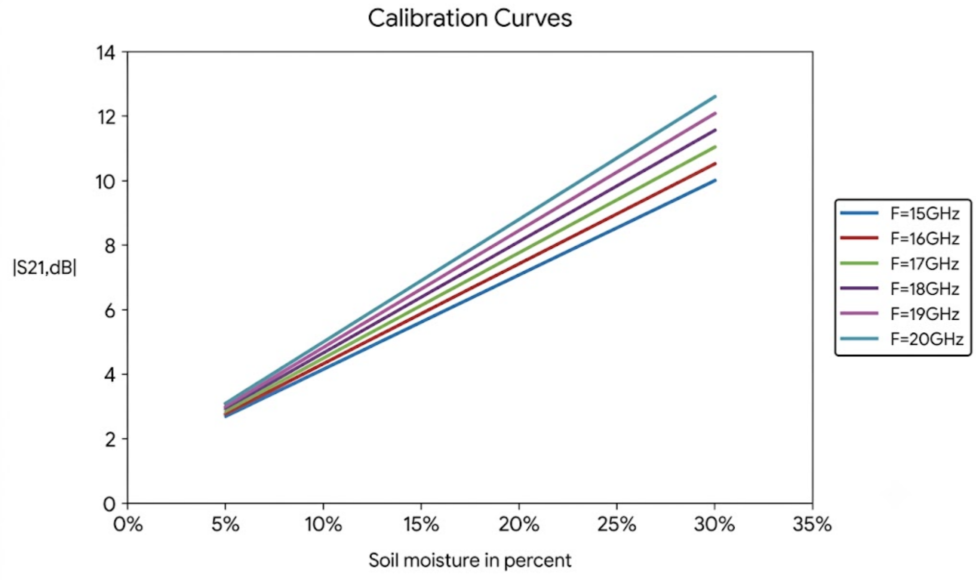

Fig. 4. Calibration curve showing the linear relationship between the transmission coefficient and the moisture level (H) in percent

The calibration results show a very regular trend with moisture content increasing almost linearly as the transmission coefficient decreases. This is a consequence of the direct role of water in dielectric losses and is an indication of how sensitive the proposed sensor is to moisture content changes. As water is added to the material, the attenuation of the propagating wave is higher and therefore the measured transmission response of the wave is different.

One of the main results of this analysis is the excellent agreement between the calibration curve and the theoretical relation developed in Section 3. The numerical results closely agree with the affine dependence predicted by the analytical model and indicate that the assumptions that were made in the theoretical study still hold for the moisture range. This is good evidence that the transmission coefficient can be used as a reliable indicator of water content.

Because of the linearity, the calibration data can be described by a simple affine model as follows:

$$H = a \cdot S_{21} + b \tag{6}$$

where (a) and (b) are calibration coefficients obtained from regression analysis of the simulation or experimental data. The coefficient (a) represents the sensitivity of the sensor, while (b) is the offset of the given operating conditions.

Once these coefficients are determined, moisture content can be estimated directly from the measured value of S21 without the need of complex electromagnetic inversion procedures. This greatly simplifies the sensing system setup and allows for accurate and real time measurements. From a practical point of view, such a calibration strategy is very attractive as it is relatively easy to use and sensitive and is not invasive. Based on these results, we show that the proposed waveguide-based sensor can provide a simple and reliable method of moisture estimation. The well-established physical basis, nearly linear response and simple calibration procedure can make it suited for applications with constant monitoring and fast decision making.

5 Conclusion

In this work, we have proposed a microwave-based method for moisture estimation with rectangular waveguide frequency range from X to K. We are able to exploit the strong dependence of dielectric properties on water content, and use the transmission coefficient S21 as the primary sensing parameter. The relationship between moisture content and microwave attenuation has been found in electromagnetic theory and numerical simulations. The theoretical model based on the propagation behavior of the dominant TE01 mode shows how the dielectric losses change the transmission response of the waveguide. Full-wave simulations have confirmed these predictions and shown the effect of moisture on the cutoff behavior and attenuation of the system. In particular, the frequency range between 15 and 20 GHz was considered the most suitable operating window with a favorable balance between transmission quality and moisture sensitivity. One of the most important findings of this work is the linear correlation between transmission coefficient and moisture content in the chosen frequency band. A simple calibration model was developed to convert microwave measurements into moisture estimates. The method avoids destructive testing and is a genuine path to contactless and real-time moisture monitoring. While the present work is concerned with theoretical analysis and numerical verification, the consistency of the analytical predictions and simulation results supports the sensing idea. It is with this in mind that we will focus on experimental validation with a dedicated waveguide measurement system and soil samples under controlled moisture conditions. Temperature, particle size distribution, material heterogeneity and measurement uncertainty will also play a role in sensor performance. In general, the theoretical rigor, numerical verification and practical simplicity of our solution point to the potential of rectangular waveguide microwave sensing for moisture characterization. Our technique is a promising alternative to conventional measurement methods and could be applied in agriculture, environmental monitoring, civil engineering, and industrial process control where reliable and non-destructive moisture assessment is necessary.

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