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Research Article

Dielectric Substrate Prediction Through Transmission Measurements and Machine Learning

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Dielectric properties of the substrates play an important role in the design and performance characterization of communication components such as antennas, filters, and sensors. Conventionally, dielectric probes are used to measure the properties of the substrate. However, the dielectric probes are very expensive and easily breakable instruments. In this work, a novel method of dielectric substrate prediction has been proposed using S_{12} measurements with two waveguides, along with the application of machine learning. Extensive data collection is done using multiple simulations of the proposed method in 3D electromagnetic software in the X-band frequency range (8–12 GHz). The measurements are then conducted by using two waveguides, and the data is compared with the simulation data set, where the decision is made based on the comparison of dielectric properties. For verification of the proposed method, dielectric substrates of FR4 and Rogers 5880 have been used, which demonstrated very close agreement between the measured properties and properties from the data sheet.

Keywords: dielectric properties; machine learning; substrate; waveguide; X-band measurements

1. Introduction

Dielectric properties of materials, specifically the permittivity and permeability, are essential for designing various electromagnetic devices, including filters [1], sensors [2, 3], and antennas [4–7]. Measuring these properties accurately is crucial for material characterization, quality control, and research and development. Different techniques have been proposed by researchers for measuring the dielectric properties of such materials [8–10]. One of these techniques is the cavity resonator method, which utilizes a resonant cavity where the material under test is placed. The shift in resonant frequency and change in quality factor are measured to determine the dielectric properties. This method is highly accurate and is suitable for lost materials. However, it can be used for only limited frequency ranges, and sample preparation is also complex [11]. The microstrip resonator method is quite like the cavity resonator method; it uses a microstrip resonator to determine the dielectric properties of the solid substrates. A microstrip resonator is a microstrip transmission line structure where standing waves are established at the resonant frequency; thus, it is used for dielectric measurement. This method includes physically depositing the material under test to the microstrip resonator and the shifts in the resonant frequency and quality factor, which are considered to be affected by dielectric constants. Its planar nature allows for easy fabrication and integration into compact systems, but precise measurements require careful

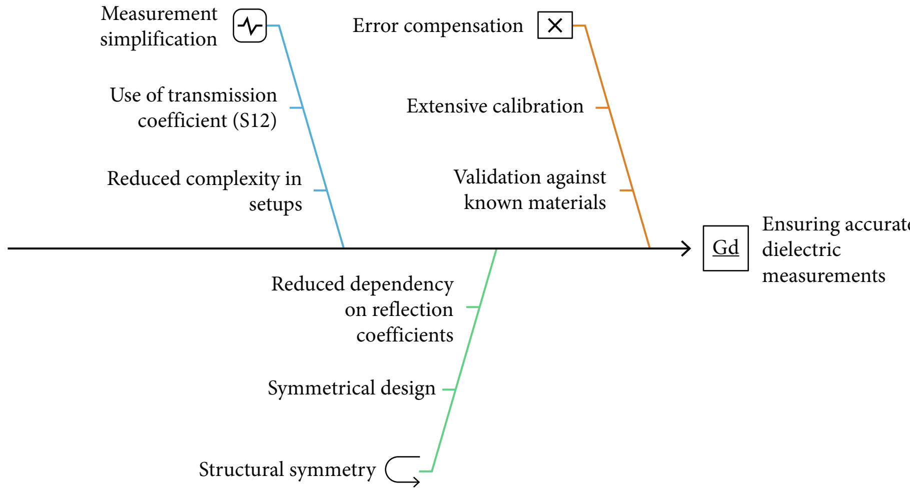

Figure 1: Overview of the employed dielectric measurements technique.

calibration and consideration of parasitic effects. When a material is placed over the microstrip, it changes the effective permittivity of the structure, thereby altering the resonant frequency. The resonant frequency and Q-factor are obtained with the material and compared with the values obtained without the material, and then, with the help of the two, the permittivity of the material is computed. Of all the transmission cavity methods, this one can work through a broad frequency range, and its appropriateness is for slender films and small specimens; nonetheless, the high-loss material's accuracy for calibration needs and its precision to indicate these losses are part of the drawbacks of using this method [12].

Another technique of dielectric measurement is the open-ended coaxial probe technique, in which a coaxial line probe is directly touched with the material. Decoupling the material's dielectric properties is based on the measurement of the reflection coefficient at the interface between the probe and the material. This is nondestructive and, as such, ideal for testing various liquids and semisolid substrates on the samples. Nonetheless, the mentioned method is less suited for low-loss materials since certain changes in the dielectric properties cannot be detected sufficiently. Hence, the open-ended coaxial probe method of characterizing materials necessitates regular calibration of the method, which, in the long run, is cumbersome and can slow down the pace of the measurements. Despite these limitations, its versatility and nondestructive nature make it a valuable tool in dielectric measurements [8, 13, 14]. The free space method has also been proposed for dielectric measurement, where the material is irradiated by a microwave antenna in free space, and its transmission and reflection are measured. This method is convenient to work with large or uneven samples and does not involve direct interaction with the dielectric substrate, which expands the number of its possible uses. However, this will highly depend on the orientation of the probe as well as other factors such as temperature and humidity. Thus, appropriate procedural configuration and management of the testing environment are highly important when applying this technique [15–17]. Waveguide characterization of dielectric materials with arbitrary shapes has also been proposed in [18], which utilizes equivalent π-circuits and neural network optimization, making the process relatively complex. The characterization of different dielectric materials has been a focus of researchers for a number of applications in wide frequency ranges [19–22]. However, the focus is generally on a specific material or frequency range, such as in [22]; the research work addresses the dielectric and magnetic properties of bismuth-substituted barium hexaferrite, which is a potential substrate for low-frequency antenna designs.

Existing dielectric property measurement techniques, such as cavity and microstrip resonators, open-ended coaxial probes, free-space methods, and waveguide characterizations, each have inherent limitations, including narrow frequency operation, complex sample preparation, calibration challenges, sensitivity to environmental conditions, and computationally intensive parameter extraction. Moreover, most methods require separate determination of permittivity and loss tangent, increasing complexity and reducing measurement efficiency, while the integration of data-driven techniques such as machine learning for simplified broadband dielectric characterization remains largely unexplored. To address these gaps, this research proposes an improved nonresonant transmission method that directly utilizes measured transmission coefficients (S_{12}) and applies machine learning to predict dielectric properties without separate parameter extractions. This approach enhances accuracy through data-driven error compensation, supports broadband applications with minimal calibration, and provides a simplified, low-cost, and efficient solution for dielectric characterization of diverse material substrates, as explained in Figure 1.

2. Methods

The technique under consideration utilizes a nonresonant transmission method for the evaluation of the dielectric constants of the materials in the X-band frequency range (8–12 GHz). This entails the design and analysis with two

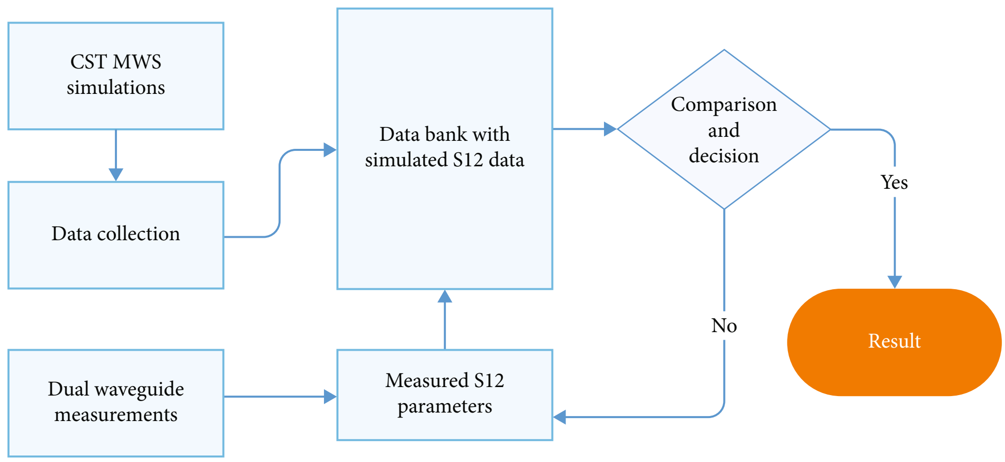

Figure 2: Proposed method of dielectric measurements.

standard waveguides, where the simulation is performed with the help of Computer Simulation Technology Microwave Studio (CST MWS). The waveguides have cross-sections with dimensions of 22.86×10.16 mm, which is standard for X-band applications. The above waveguides are excited from an excitation port situated at one end of the waveguides for the introduction of electromagnetic waves through the system. Its primary aim lies in determining the transmission coefficient, which is an important characteristic of materials serving as the subject of study of the given technique. A large set of simulation data with 110,000 unique samples consisting of S_{12} parameters is collected in this way and is stored in a data bank. The data has been collected using simulations of the proposed setup in CST MWS, considering the dielectric materials' permittivity (ε_r) ranging from 2 to 13 and loss tangent ($\tan\delta$) varying from 0.0001 to 0.10. The variation resolution for ε_r is 0.1, while for $\tan\delta$, the resolution was much smaller at 0.001 to obtain the data as accurately as possible. The values have been considered, taking into account possible dielectric materials used for electromagnetic applications. This range also allows our system to be broadly applicable for materials relevant to microwave and millimeter-wave systems.

In addition to the simulations, a matching hardware experiment is constructed to directly determine the (transmission from Port 1 to Port 2) S_{12} parameter for each dielectric sample. The measurement setup mimics the simulated environment to gather real-world data without deviations. Ensuring that each sample is located between two of the waveguides, the S_{12} parameter, which quantifies the transmission coefficient from Port 1 to Port 2, is determined. It has to be noted here that the proposed waveguides are constructed using solid aluminum blocks with smooth surfaces, and it was established that the thickness of the waveguides does not significantly affect the results, whereas the length was kept as multiples of wavelength to determine the S_{12} magnitude across the frequency range as input to the estimation model. The key idea is that the magnitude response carries implicit signatures of both ε_r and $\tan\delta$ when swept over a broad frequency range. While this may not be sufficient for precise analytical inversion, it is sufficient for machine learning–based pattern recognition. The machine learning model effectively learns complex nonlinear mappings between the magnitude-only S_{12} response and the dielectric properties.

The measured data from this setup is systematically recorded and transmitted to the data bank for further comparison and evaluation. In the data bank, the measured S_{12} data is postprocessed by analyzing the simulated results in order to find an accurate match. This comparison becomes important in the validation of the numerical simulations in order to check whether the values obtained experimentally are consistent with theoretical predictions. That is, for each of the tested materials, by finding the closest pairs of correspondents in the table, the researchers will be in a position to confidently determine the dielectric permittivity of the substance. Finally, the values of dielectric permittivity are given out, with significant accuracy, to show the electromagnetic properties of the material. Figure 2 shows the whole process of the proposed measurement technique.

The proposed technique uses a two-port waveguide setup, where the slab is inserted between two identical symmetric waveguide sections. The two-port approach allows the user to extract the transmitted S_{12} parameter more cleanly without reflections from the measurement port affecting the results. If a single waveguide is used, it would be much difficult and error-prone to extract S_{12} for different samples of dielectric substrate. It would require an extra cavity, which can be only a fixed size. While in the proposed setup, measurement samples of different thicknesses can be used by inserting them between the two waveguides, tightly held through bonding screws.

Furthermore, the proposed method has been demonstrated for solid substrates only, but for its application to liquid materials, a slight adjustment must be made in the hardware by adding a cavity to contain the liquid. However, it should be kept in mind that the cavity material should be of a dielectric substrate, and the effect of that dielectric must be taken into account, as it will cause the effective dielectric permittivity to be different compared to the actual permittivity of the liquid. Therefore, some standard calculations and calibrations will additionally be required to measure the liquid dielectric materials using the proposed approach.

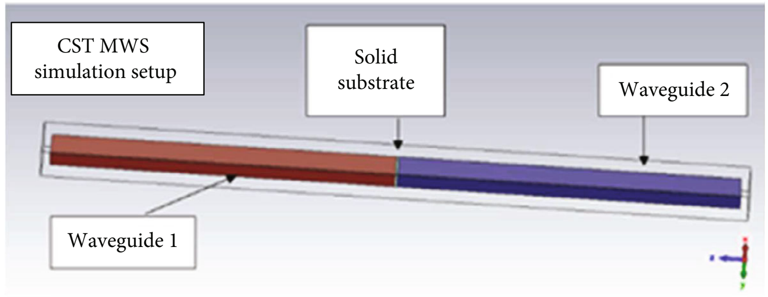

FIGURE 3: Simulation setup with two waveguides and a dielectric slab placed between them.

3. CST MWS Simulation Setup

For the simulations of the proposed setup, two X-band waveguides have been created in CST MWS, and a piece of dielectric slab is inserted between the two waveguides in a precise manner. Placing this slab helps to provide the point of connection between the electromagnetic fields with the material. When the electromagnetic waves pass through the dielectric slab, some of the waves are absorbed by the material. This absorption leads to attenuation of the transmitted and the received waves and hence creates a measurable phase delay that offers the necessary data regarding the dielectric constants of the material. The amount of absorption is directly proportional to the electrical characteristics, including permittivity and permeability of the material.

The simulations are conducted several times with slabs of different dielectric characteristics to provide a massive set of data. This has the advantage of capturing much data of different forms relating to the characteristics of the material in question. Every simulation run is based on a change of the dielectric properties of the slab, with the corresponding transmission coefficients stored. This iterative process creates a large set of data, often referred to as "big data," which is important for elaborate comparison at a later stage. Figure 3 shows the simulation setup used in this work.

Open boundaries have been used for simulation with waveguide ports on one end of each waveguide. The thickness of the waveguides was kept at 2 mm, while the length of each waveguide was kept at $10\,\lambda$. The typical S_{12} results based on the simulation of two dielectrics with different material parameters are demonstrated in Figure 4. Essentially, it is necessary to emphasize that, as a rule, dielectric characteristics of substrates are characterized by the permittivity (ε_r) and loss tangent ($\tan\delta$). These parameters are based on the real and imaginary parts of permittivity. The use of the complex factor ($\tan\delta$) means that the ratio of the imaginary part to the real part, where the former symbolizes the dissipation of energy inside the material and the real part the energy storage. A higher $\tan\delta$ indicates that the substrate's ability to absorb the electromagnetic energy passing through it is enhanced, whereas the ε_r value primarily influences the resonant frequency of the structure. In Figure 4, it can be observed that a sample with higher ε_r and $\tan\delta$ exhibited a more significant negative value of absorption (S_{12}) in the simulated setup. This observation aligns well with the theoretical expectation that materials

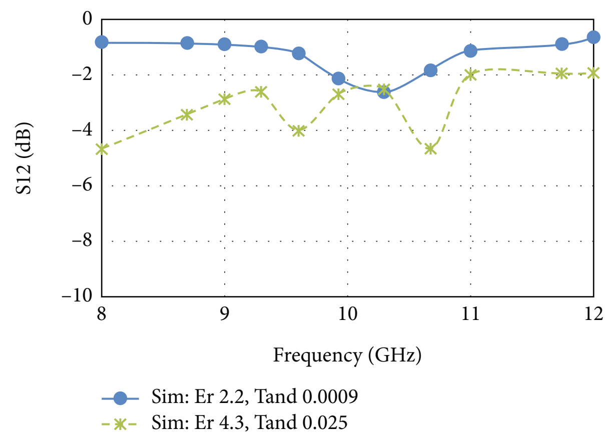

FIGURE 4: Sample of simulated S_{12} for two different dielectric properties.

with higher ε_r and $\tan\delta$ will absorb more electromagnetic energy, thereby decreasing the transmission coefficient (S_{12}).

The S_{12} parameter, which measures the power transmitted from Port 1 to Port 2, becomes more negative as the material absorbs more energy, indicating higher losses. To elaborate, permittivity (ε_r) influences how much the material polarizes in response to an applied electric field, thereby affecting the phase velocity of the wave propagating through the material. Materials with higher ε_r tend to slow down the wave more, leading to a shift in the resonant frequency of the system. On the other hand, the loss tangent ($\tan\delta$) is indicative of dielectric losses within the material. A higher $\tan\delta$ means that a larger portion of the electromagnetic energy is converted into heat, rather than being transmitted through the material. Therefore, the current relationship between ε_r and $\tan\delta$ and S_{12} is useful when designing materials for a certain electromagnetic application. For example, in the applications where signal losses have to be minimized, low $\tan\delta$ materials are chosen so that maximum energy is absorbed. On the other hand, in uses such as in electromagnetic interference and microwave absorption, high $\tan\delta$ is preferred so that the electromagnetic waves can be well damped.

Thus, the simulated results shown in Figure 4 are quite illustrative of these principles, where S_{12} for material with ε_r (4.3) and $\tan\delta$ (0.025) is higher because it absorbs more energy as compared to the other material (ε_r (2.2) and $\tan\delta$ (0.0009)). By reducing or increasing the dielectric constants ε_r and the dielectric loss tangent tan δ in the simulations, one gets an opportunity to study the effects of changes in the values of ε_r and tan δ on the waveform of the electromagnetic wave propagating through the material. Often, such an analysis is characteristic of material science and engineering, where the exact control over the material characteristics can provide improved behavior in corresponding technological usage.

4. Hardware Setup and Validation

The standard X-band waveguides were used to carry out measurements on various dielectric samples. For this purpose, two standard X-band waveguides were used, which are connected with a multiport vector network analyzer (VNA) via coaxial cables and waveguide-to-coax adaptors. The experimental setup is illustrated in Figure 5. Particular attention was given to tighten all connections in order to eliminate any unwanted noises that might interfere with the measurements. Specifically, for each dielectric sample, which is made up of substrates of different materials, the sample was carefully placed and clamped hard between the two waveguides for the measurements. The usage of X-band waveguides (8–12 GHz) is imperative since the aforementioned frequency range exhibits maximum accuracy in determining the dielectric constants of excessively utilized materials in antenna design, radar systems, satellite communications, and other related technologies. The VNA also has a key role of accurately determining the S parameters, which include the S_{12}, which represents a transmission coefficient from Port 1 to Port 2.

Closely connected to the dielectrics and properly positioned in terms of the experimental geometry, the measurements introduced are highly accurate. This precise procedure is useful in getting accurate information that can be compared with the simulated data to confirm the credibility of the experimental results of the dielectric property measurements.

A comparison of simulation results with experimental data is depicted in Figure 6. The experimental measurements were conducted on two well-known dielectric substrates of Rogers RT/Duroid 5880 and FR4. These substrates are commonly used in numerous applications and contain significant differences in the dielectric constants; they are thus suitable for this research.

The measured data of the substrates under investigation were documented and later forwarded to a general database. The latter is a data bank of values obtained from different iterations of simulations, as shown in Figure 2. This huge amount of data, in turn, was collected and compared in order to verify the correspondence between the simulation models. This data bank contains the values of thousands of simulated data which helps in the accurate identification of the data source and for comparing the measured data. The measured values could then be compared to the set of simulated data, and it would then be possible to determine the extent to which the proposed model would provide accurate results of real-life conditions.

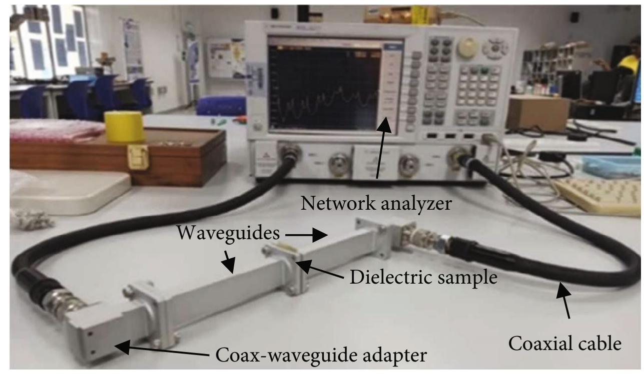

FIGURE 5: Measurement setup with waveguides connected to a network analyzer.

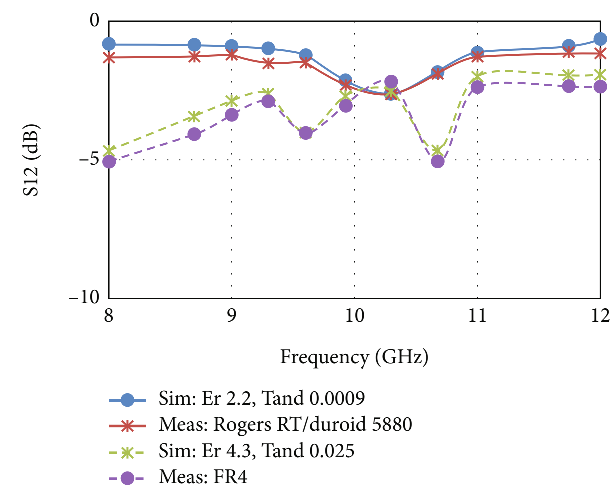

FIGURE 6: Comparison between simulated and measured results.

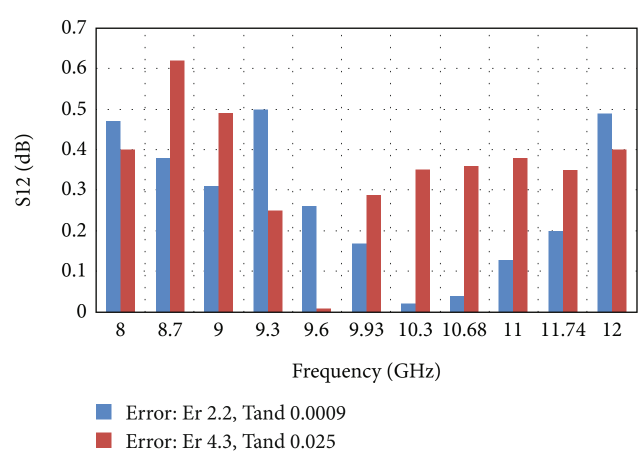

FIGURE 7: Degree of error for the proposed setup.

After the comparison of simulated and measured data, a decision was made showing the simulated and measured results. It was demonstrated that, as per expectations, the measured values of the two samples were matched closely to the simulated values of samples that contain the dielectric properties (ε_r and tan δ) of RT/Duroid 5880 and FR4.

Figure 7 depicts an overall estimation of the degree of error for the proposed setup, analyzed by the simulations and measurements. It can be observed from Figure 7 that in this case, maximum discrepancy of 0.5 and 0.6 dB occurs for RT/Duroid 5880 ($\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$) and FR4 ($\varepsilon_r = 4.3$ and $\tan\delta = 0.025$), respectively. The correct forecasting of their dielectric properties proves the efficiency of the proposed technique. The results of the comparisons between the values obtained from calculations and from simulation indicate the reliability of the theoretical models and the measurement methods adopted here. This validation is paramount particularly to the progress of material sciences and to confirm that what is theoretically predicted corresponds with the observed experimental results.

5. Conclusion

The verification of an innovative technique, which is precise and relatively cheap for the determination of the type of dielectric substrates, has been made, and it has been noted that the error is minimal when computational and experimental approaches have been adopted systematically. With reference to the results of the validation procedure, including the detailed comparison of simulation outcomes with measurements, it is possible to state that this approach is rather effective and accurate. The described method is then applied to various types of dielectrics and at various frequencies using standard waveguides and a VNA. Due to this flexibility, the method is applicable in any field, ranging from telecommunication all the way to material science. This concept can be applied to a wide variety of dielectric materials, and as such, this makes it a generalized case for researchers and engineers. It provides a highly effective, accurate, and versatile means of quantifying the dielectric substrates without going into the extensive, complex, and real permittivity calculations. Besides, the technique also makes it possible to select the proper dielectric materials depending on the application and enhance both the final device characteristics and efficiency. This validation proves that the method can indeed be applied in real-life problems, with assurance of the results that shall be derived. Overall, this approach represents a significant advancement in the field of dielectric measurements, offering a reliable and versatile solution for material characterization.

Data Availability Statement

The data used to support the findings of this study can be obtained by contacting the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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