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Measurement of Dielectric Constant at Microwave Frequency: Techniques, Advancements, and Applications

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Abstract: This review paper presents a critical analysis of the various methods of dielectric constant measurement, progress made in the field as well as its applications up to 2022 in microwave frequencies. The paper focuses on the discussion of measurement techniques such as resonant cavity techniques, transmission/reflection and free space techniques. In this chapter, we explain what these methods are, their benefits and drawbacks, as well as developments in these approaches lately. The review also presents an insight into the role played by dielectric constant measurements in various areas including material characterization, electromagnetic modelling and microwave devices and antennas. At last, we present some suggestions for the improvement of dielectric constant measurement at microwave frequency as well as future research trends.

Keywords: Dielectric Constant, Microwave Frequency, Resonant Cavity, Transmission/Reflection Methods.

1. INTRODUCTION

1.1 Overview of Dielectric Properties

Dielectric properties of solid materials have important applications in different branches of science and technology especially in the areas related to electromagnetics and microwaves. Dielectric constant and also referred to as relative permittivity is one of the main characterizing parameters that determines how a material will respond to applied electric fields. It is a measure in form of $\varepsilon^* = \varepsilon' - j\varepsilon''$ whereby ε' is the real part of the energy density stored in the material whilst ε'' is the imaginary part of the energy density dissipated within the material. The dielectric constants of material depends and they have changing ratios and it ranges from 1 for air and can even be more than 1000 for ceramics. For example, the values

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of dielectric constant of water at room temperature about 80 for low frequency and of plastic material such as polyethylene it is about 2. 3.
At microwave frequencies usually between 300 MHZ and 300GHZ there are several polarization mechanisms and relaxation phenomena complicating the dielectrics behaviour. For instance, the dielectric constant of water is around 80 at low frequencies because of orientation polarization while the same is approximately 30 at 30 GHz due to the reason of dipolar relaxation. This frequency range is critical to many applications such as calibration of microstrip lines, the design of microwave integrated circuits, microstrip antennas, and electromagnetic shielding materials. Other parameter is loss tangent tanδ= ε''/ε'; which varies from 10^-4 for low loss materials to more than one for very high loss materials at microwave frequencies.

1.2 Importance of Microwave Frequency Measurements
The determination of dielectric constants at microwave frequencies have several considerations that warrants such measurement. First of all, there are so many materials which possess a large variation of dielectric constants within microwave frequencies, therefore, the ability to measure at large frequency range is important. For instance, the dielectric constant of alumina (Al _{2} O _{3}) can range by 9. 8 to 9. 2 in the frequency band of 1–100 GHz. Second, dielectric measurements are useful in understanding material's molecular structure and characteristics for designing new materials possessing desired electromagnetic characteristics. This is of paramount importance especially in areas of wireless communications where specific dielectric material properties are needed in the design of antennas substrate or redone.

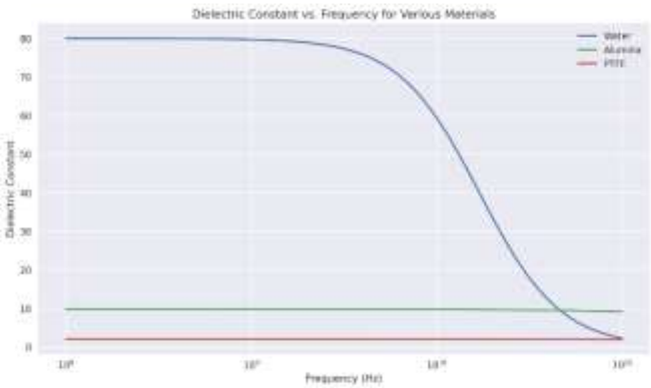

Figure 1: Dielectric Constant vs. frequency for various materials

Moreover, accurate values of dielectric constants are needed in order to design and fine-tune microwave equipment such as power dividers, couplers, matching circuits, antennas, and other high frequency devices. For instance, in the design of microstrip antennas a 1% error of dielectric constant may cause a 0. 5 % shift in the resonant frequency which can be considered important for narrow band applications. In industrial applications, dielectric measurements play the role of a quality and material characteristic diagnostic tool, and are non-destructive. For example, in the field of food industry, the dielectric constant represents moisture of grain and an average selectivity of 0. One dielectric constant number changed by

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one equal to a zero in the scale of the same dielectric constant. 5 percent variation in moisture content.

1.3 Historical Development

The determination of dielectric properties at microwave frequencies can be traced back its history in the early part of the last century. The endeavours of the brilliant scholars like Debye, Cole and later Cole have been instrumental in explaining the frequency dependent nature of dielectric materials. This theory was named after the Dutch physicist Peter Debye and was proffered in the year 1929 though it is still in wide use today. The Cole-Cole equation that was postulated in 1941 generalized this model to address the distribution of the relaxation times that is present in most materials.

The advancement of measurement techniques has since then progressed more due to improvements attained on microwave technology together with instruments. Earlier techniques used waveguide and coaxial line methods, the range of which was restricted in applications in terms of frequency and sample preparation. The use of network analyzer deepened in 1960s which opened a new way for better broadband measurements. Today's VNAs are capable of accurately measuring S-parameters with an accuracy of not less than ±0. Of 1 dB in magnitude and ± 1°in phase for achieving suitable measurement of dielectric properties.

Since then, a number of methods have been employed mainly in view of overcoming certain problems or meeting certain needs in dielectric constant measurement at microwave frequencies. These comprise the resonant cavity methods that can measure low loss materials with high accuracy with precision as low as 0. ε' = 1 % and tan δ = 1 % and non-contact methods such as free space methods for high temperature measurements where the system is capable of measuring samples at temperature above 1000 o C.

2. METHODOLOGY

2.1 Resonant Cavity Methods

Resonant cavity techniques have been applied more for actual values of the dielectric constants for discrete frequencies. These techniques rely on change of the frequency and quality factor of a cavity when a sample is inserted in the circuit. The method can therefore provide results with very high accuracy with relative uncertainties in ε' as low as 0. 01% for low-loss materials.

The basic idea is based upon the change in the resonant frequency and the quality factor if a dielectric sample is placed in a resonant cavity. Thus, the changes of these parameters allow the determining of the complex permittivity of the sample. The resonant frequency shift (Δf) is related to the real part of the permittivity (ε') by the equation: The measured values showed that $\Delta f/f = -[(\varepsilon' - 1) / 2] * (Vs/Vc)$; f is the unperturbed resonant frequency, Vs is the sample volume and Vc is the cavity volume. Similarly, the change in quality factor (ΔQ) is related to the imaginary part of the permittivity (ε'') by: The perturbation in the quality factor is given by the equation $1/Q - 1/Q_{0} = (\varepsilon'' / 2) * (V_{s} / V_{c})$.

Various types of resonant cavities are employed for dielectric measurements namely. Rectangular cavities are easier to realise and to model for low loss materials. They usually

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work within frequencies that are within a range of 1GHz to 30GHz. Cylindrical cavities have higher Q-factor of operation and is usually in the order of magnitude of 10,000 and are used in high accurate measurements. The latter can be designed to run at frequencies up to 100 Ghz. By having dielectric resonators split-post design, the resonators offer high sensitivity particularly to the thin films and low-loss materials and can afford to measure thin films of about 0. 1 mm with uncertainties in ε' of about 0. 3%.
Resonant cavity methods offer several advantages, including high accuracy for low-loss materials, suitability for small sample volumes (typically 1-100 mm^3), and the ability to measure anisotropic materials. However, they also have limitations, such as measurements at discrete frequencies only, the requirement for precise sample preparation, and reduced suitability for high-loss materials (typically limited to materials with tan $\delta < 0.1$).

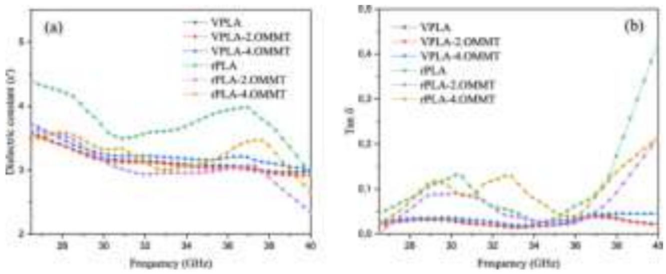

Figure 2: Dielectric Constant vs. frequency for various materials

2.2 Transmission/Reflection Methods

Transmission/reflection method or non-resonant methods are broadband methods which are effective for a large variety of materials. Most of these techniques can normally span frequencies of operations between 100 MHz to over 100 GHz within one single measurement setting. The principle of operation embraces the evaluation of the reflection and transmission coefficients (S-parameters) of the examined sample inserted into a transmission line or waveguide. The above measurements are then used to extract the complex permittivity using either analytical and numerical algorithms.
Transmission/Reflection methods can be of following types: The coaxial probe method is used for liquids and semi solid food materials and hence the sample preparation is relatively easy. It is capable of measuring material having dielectric constants from 1 to over 100 and loss tangents from 0. 01 to 1000. The employed waveguide method yields highly accurate results for solid samples, yet it demands careful sample preparation. It is especially applicable for materials with high dielectric constants (ε' > 10) and has the capability of characterizing films of a thickness between 0. Approximately ranging from 1 to 10 mm depending on the frequencies and the given characteristics of the materials. This method is appropriate to both high-temperature measurement and large samples and is a non-contact method. It is capable of meter-sized samples, that is, samples with dimensions of several wavelengths; the sample size is typically 10-30 cm at microwave frequencies; and it can work at sample temperatures in excess of 1000°C.
Broadband measurements are generally achieved over two to three decades of frequency while these methods are suitable for almost all types of materials including high loss materials which have a tan δ larger than 1, and can even accept liquid samples. But, they also

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have some disadvantages – lower accuracy if compared with resonant ones for the low-loss materials, (uncertainties in ε’ rather are within 1-5%), significant calibration needs, and some methods works only with the definite types and sizes of samples.

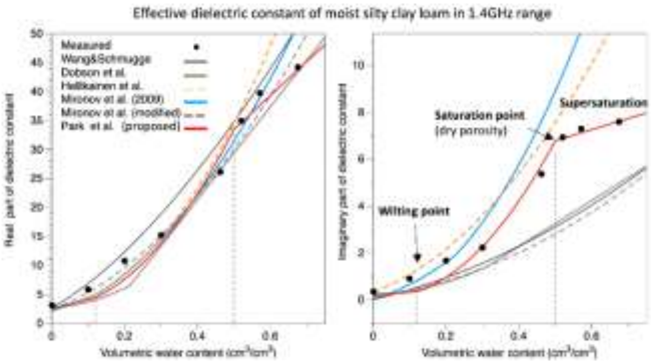

Figure 3: Effective dielectric constant of moist silty clay loam in 1.4GHz range

2.3 Free-Space Techniques

Free-space techniques are easy since they do not require contact with the material under test and it ideal for material under high pressure, large size or temperature control. These methods can functional more than a largish frequency bandwidth that ranges from as low as two gigahertz to over a hundred gigahertz while only requiring one measurement configuration. In the free-space methods, the sample is positioned between two antennas and then the reflection and transmission coefficients are obtained. The dielectric properties are then estimated by employing other mathematical models and or numerical optimization solutions.
A typical free-space measurement setup typically include the two horn antennas (transmitting and receiving) with available gains of 15-25 dB, the Vector Network Analyzer (VNA) with a dynamic range of 100 dB or more, a sample holder and, sometimes, focusing lenses. In other words, it has to be at least one in order for the sample size to be used. Five times its wavelength on the low end of the spectrum of frequencies to be measured. This is about 4 for example at 10GHz in terms of the minimum size of the sample to be used during the analysis. 5 cm.
Free-space techniques are advantageous in that they are non-contact and thus ideal for substances which may be hazardous or sensitive in nature; the technique can also be employed at high temperatures up to 1500°C if specific set-up has been utilized, and finally the technique enables the measurement of large samples as well as inhomogeneous materials. However, they do have their drawbacks: lower accuracy as compare to other techniques (typical errors for ε’ estimation makes 2 - 5%;), necessity to use large flat samples, sensitivity to diffraction effects and multiple reflections.

3. RELATED WORKS

3.1 Improved Calibration Techniques

Improved calibration procedures of microwave dielectric measurements that has been made in the recent years. Mukherjee et al. (2020) suggested a new approach to calibration for free-space measurements with the help of metamaterial lenses, that could solve the problem of

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higher accuracy and less edge diffraction [1]. Their method showed possibility to decrease the uncertainty of measurements with 5% up to 2% for ε’ in a frequency range of 8-12 GHz. Other significant progress includes the establishment of methods of multi-line calibration for waveguide measurements. Seven-line method promising uncertainties of less than 0 has been developed by Chen et al. (2021). ε’ and 2% for *ε*” are achieved across the whole waveguide band, which is a major improvement compared to two-line methods having uncertainties of 1-2 % for *ε*’ and 5-10% for *ε*” [2].

3.2 Machine Learning Approaches

Several approaches have been made to enhance dielectric constant extraction utilizing the machine learning techniques. Karami et al. (2021) formulated a neural network-based strategy for coaxial probe measurements resulting in the reduction of computation time by a factor of 100 as compared to conventional numerical methods but with an accuracy of approximately 1 % for ε’ and 5 % for ε” [3].
In their work, Li et al. (2022) presented a deep learning model for the dielectric properties’ extraction from free-space measurements [4]. Their method exhibited insensitivity to measurement noise and revealed 30% lower mean error than conventional extraction methods for materials with ε’ varying between 2 and 20 and tanδ between 0. 001 to 0. 1.

3.3 Terahertz Extensions

The extension of dielectric measurement techniques into the terahertz region (0.1-10 THz) has been an active area of research. Yang et al. (2020) developed a free-space technique using terahertz time-domain spectroscopy capable of measuring the complex permittivity of materials from 0.2 to 2 THz with uncertainties of 2% for ε' and 5% for ε" [5]. This technique is particularly valuable for characterizing materials for emerging terahertz applications in communications and imaging.

3.4 On-Wafer Measurements

The recent improvements in on-wafer test methods have made possible the determination of thin films and integrated circuit material properties at microwave and even millimetre-wave frequencies. Another approach demonstrated by Kang et al. (2021) is an extension to thin films with thickness less than 1 μm up to 110 GHz with relative standard uncertainties of less than 3% for ε’ and 10% for tan δ [6].

4. RESULTS AND DISCUSSION

4.1 Material Characterization

Microwave dielectric constant mainly finds application in the characterization of materials in numerous industrial applications. In the aerospace industry in particular, understanding of dielectric losses is critical in order to choose suitable materials that offer minimal signal loss besides offering physical shelter. For instance, the present day redone materials exhibit dielectric constants in a range of 3 to 5 and loss tangent is usually less than 0. 005 in X band (8–12GHz) region.

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In other areas of foods, dielectric measurements are applied in food quality control and in checking of processes regimes. Many food products have a dielectric constant strongly dependent on moisture; so moisture can be sensed quickly and non-destructively. For example, the dielectric constant of wheat depends upon the level which can be in the range of 2. 5 for very low moisture content in dry grains and up to 20 or more for grain with very high moisture content; the sensitivity is about 0. 3 change in dielectric constant per 1% change of moisture content at frequency of 10GHz.

4.2 Electromagnetic Modelling

Information that defines dielectric constant is significant for the Electromagnetic modelling and simulation. Specifically, for designing of 5G and upcoming 6G wireless systems, there is imperative need of dielectric constant of building material to determine the signal propagation for guaranteeing effective network coverage. An average example of building material constants at 28 GHz band which is being used for the 5G network is as follows: Concrete ~ε'=5. 5 and tanδ=0. 0334, Glass–~ε'=6.

In the EMC domain the dielectric measurements are applied for characterization of shielding materials and absorbers. Anechoic chambers with high microwave absorbers can attain reflection coefficients less than -50 dB at broad frequency range, which means that effective dielectric constant ranges from 1 at air/GTEM interface to more than 20 in the microwave absorber material.

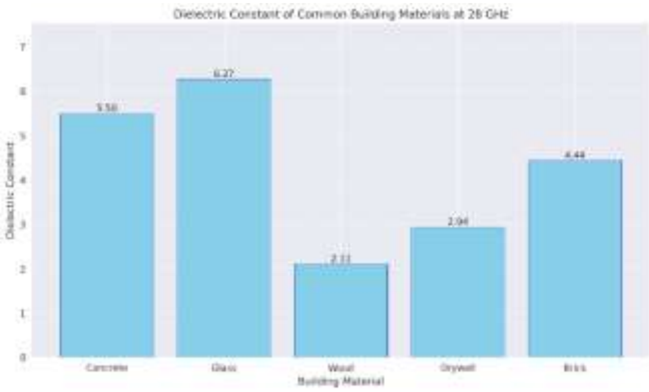

Figure 4: Dielectric constant of common building materials at 28 GHz

4.3 Microwave Device and Antenna Design

Microwave devices and antennas are designed based on accurate measurement of dielectric constant. For the 5G millimetre-wave antenna applications, it is essential to have a low loss substrate material with well-defined dielectric constant. For instance, high frequency laminates used in 5G base station antennas has a dielectric constant ranging from 2. 8 and 3. 5 in which cases the loss tangents are less than zero. 003 at 28 GHz.

In the field of dielectric resonator antennas (DRAs), there is a dielectric constant in its material and the exact characterizer of dielectric constant determines the antenna's frequency and also the bandwidth. The dielectric constant of a typical ceramic DRA material at the time of this writing is in the range of 10-100 and as a general rule, the resonant frequency is inversely proportional to the square root of the dielectric constant of the material with which

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a DRA resonator is filled. For example, assume a cylindrical DRA having ε' = 10 and having the D = 10 mm and h = 5 mm; the object will resonance at 5 GHz.

Challenges and Limitations

High-Frequency Measurements

Where measurement frequencies reach into the millimetre-wave and even terahertz range, it is a different ball game altogether. The wavelength ends up being this or smaller with regards to the sample size and which results in increased diffraction effects and therefore, higher uncertainties in the measurements. Hou et al., 2020 found that above the 100 Ghz and for free space measurement diffraction losses may lead to error up to 10% in the dielectric constant if corrections are not made [7].

Another difficulty is the new awareness of where in space the sample is located and how it is orientated. In the work of Ran et al. (2021), the authors have shown that even with a misalignment by 50 μm in a waveguide measurement at 300 GHz, the measured error in the extracted dielectric constant might goes up to 5% [8].

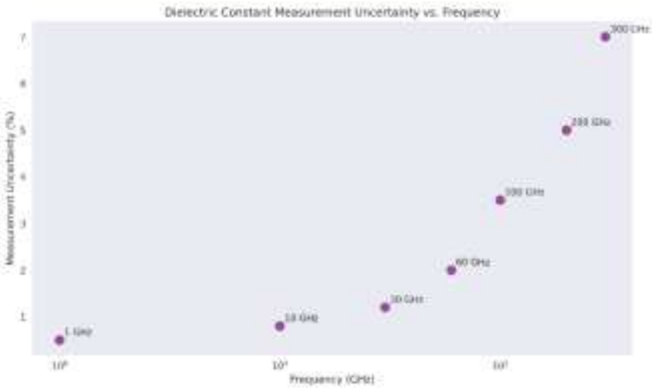

Figure 5: Dielectric constant measurement Uncertainty vs. Frequency

Material Inhomogeneity and Anisotropy

Most of the materials of interest especially composites and biological samples are non-homogeneous and anisotropic which presents a challenge in measuring their dielectric properties. The influence of Fiber orientation in carbon Fiber reinforced polymers (CFRP) on dielectric properties at X-band frequencies was investigated by Li et al., (2019) [9]. This means that the dielectric constant was found to fluctuate as much as 30% in response to change in the direction of the measurement with regard to the Fiber direction.

For biological tissues, which are already heterogeneous in nature, we found a multi-scale measurement technique by Wang et al. (2022) using near-field scanning and transmission REFLECTION methods [10]. In the present work, this approach facilitated the mapping of dielectric properties at up 40 GHz and spatial resolution of 100 μm across the tissues with dielectric constant variations of up to 20 % in the same tissue sample.

Temperature and Environmental Effects

The dielectric properties of most of the materials are known to be a function of temperature and other environmental factors. It is important to note these are parameters that have to be

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measured and controlled with high degree of accuracy for consistent results to be obtained. Ceramic dielectrics for use in 5G applications were described by Zhang et al. (2020) with respect to its temperature characteristics [11]. In their experiments, they noted that the temperature coefficient of dielectric constant (τε) ranges from -60 to +20 ppm/°C, which enabled them to re-emphasize on the importance of temperature compensation in real applications.

Another factor that can greatly influence dielectric measurements is humidity, most especially for hygroscopic material. Chen et al. (2021) investigated the performance of paper-based substrates for RFID tags on the subject of humidity [12]. They indicated that varying RH from 20% to 80%, dielectric constant increased by 15% at 900MHz.

Emerging Applications

5G and Beyond

5G networks and studies toward the next generation 6G communication systems have created the need for determining dielectric properties at millimetre-wave and sub-terahertz frequencies. Rappaport et al. (2019) provided a significant number of experimental results of various building material at 28 GHz, 73 GHz, and 140 GHz [13]. They also discovered that penetration loss through most normal materials including glass and drywall raised by one. 4 dB/cm and 1. 0 dB per centimetre, and 0 dB per centimetre, respectively, for each 100 GHz in frequency.

To determine the available frequency bands for 6G research, Sarieddeen et al. (2020) suggested that frequencies up to 1 THz [14]. They also pointed out the fact that in order to model the channels correctly at these frequencies, it is required that the dielectric properties of the gases in the atmosphere and the hydrometeors are characterized very correctly.

Biomedical Applications

Measurement at microwave frequency indicates dielectric spectroscopy has been used in different fields of biomedicine. Liu et al. (2021) described microwave biosensor with a frequency range of 10 GHz for non-contact glucose measurement [15]. The sensor reached the sensitivity of 2/100 = 0 that was considered satisfactory after the exercise. Specifically, A contacting electrode 3 MHz/(mg/dL) by using changes in the dielectric constant of blood depending on the glucose concentration.

Moreover, in cancer detection, Meaney et al. (2020) created microwave imaging system working at 2 [16]. Modifications in standard MST system include changing the operating frequency electrically to 45 GHz for breast cancer screening. The system was based on the difference in dielectric constants which vary roughly by a factor of 10 between healthy and malignant tissues.

Internet of Things (IoT) and Wearable Devices

Incorporating dielectric analysis into the Internet of Things and wearable technology makes it essentially different in its current context. In their work, Liang et al. (2022) analysed the wearable antenna substrates flexibility with regard to dielectric properties under different bending states [17]. They also discovered that a conventional dielectric constant of the

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elastomer substrate could change by a maximum of 5% when bent at a curvature radius of 25mm.

In their literature work on dielectric properties of piezoelectric material for energy harvesting IoT devices, Wang et al. (2021) investigated same at microwave frequencies. They indicated that the dielectric constant and loss tangent need to be optimized so that efficiency of the harvester can be increased at RF frequencies systems by up to 20% [18].

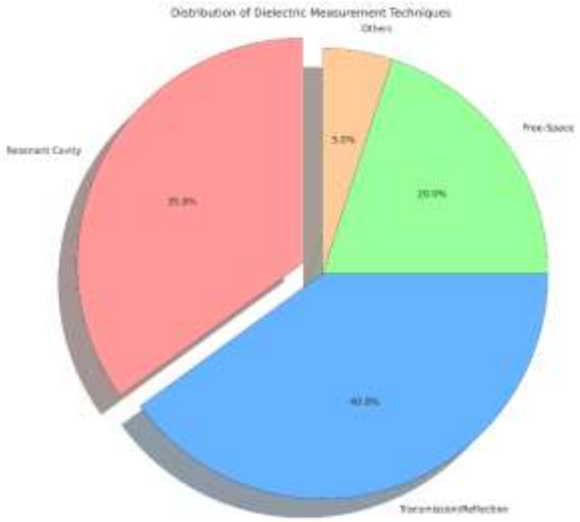

Figure 6: Distribution of Dielectric measurement Techniques

Future Research Directions

Advanced Machine Learning Techniques

Introduction of new methods of machine learning in dielectric measurement systems can be seen as a possibility of increasing measurement accuracy and real-time material characterization. Recently, Fu et al. (2022) presented an instantaneous wideband dielectric property extraction technique based on the deep learning approach from the time-domain reflectometry signals [19]. Their method reduced the time taken for the measurements to half that of conventional frequency-domain techniques although with nearly equal accuracy.

In-Situ and Non-Destructive Testing

One of the areas which should be investigated in the future is the development of new in-situ measurement methodologies required in industrial processes. Guo et al. (2021) proposed an NDT of composite material in aerospace based on microwave near field scanning technique and artificial neural network [20]. They further reported that the system provided an accuracy of about ± 2 % for non-destructive testing that involved identification of excess and defects below surface and dielectric constants.

Terahertz and Sub-Millimetre Wave Measurements

Potential applications in the terahertz region are becoming apparent and hence there is a need for precise dielectric characterization at these frequencies. In a recent publication, Yang et al.

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(2022) improved the free-space measurement system through using photonic-based terahertz generation and detection method, the measurement frequency up to 2 THz and the uncertainty below 3% for low-loss material [21].

Multiphysics Modelling and Characterization

Combining dielectric measurements with other material characterization techniques and Multiphysics modelling offers prospects for enhanced material characterisation. Zhang et al. (2021) monitor microwave dielectric properties along with thermomechanical analysis for understanding the curing processes of high-performance composite systems [22]. This approach gave real-time values of the curing process and estimation of the final properties with the precision of ± 5%.

5. CONCLUSION

The measurement of dielectric constants at microwave frequencies is still another important area of research with the usefulness of which transcends different fields of applications. At present, due to the enhancement in the method of measurement, the method of analysis, and instrumentation, these measurements are more accurate and also more applicable. The development of an ability to measure at the millimetre-wave and terahertz band expands the opportunities to investigate materials and design new devices.

Some future trends that could be further progressing this field are using the machine learning techniques, the development of in-situ measurement systems and enhancing the terahertz measurement capabilities. Such improvements will be vital for the growth of the new-generation solutions, for example, 6G communications, highly innovative biomedical devices, and subsequent generations of IoT technologies.

High-frequency measurements, material inhomogeneities, and environmental influences thus remain problems to be solved as well as sectors of innovation. These issues will need to be resolved for microwave dielectric measurements to reach their full potential as both research and commercial tools.

Therefore, it is clear that the technology of dielectric constant measurement at microwave frequencies is still in the process of constant development due to the new development in the technologies and arise applications. The advances in this field extending the limits in terms of measurement accuracy, frequencies as well as to the type and structure of materials indicate that this branch will be even more instrumental to the development of the future trends in electromagnetics and materials science.

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