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Dielectric Material Measurement Method: A Review

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***Abstract*— Non-destructive testing (NDT) is one of many techniques that have been developed over the years to facilitate the process of evaluating and inspecting material properties in a wide range of applications. These techniques can be used on materials such as metals, ceramics, composites, and coatings to assess the material properties without modifying the entire properties and damaging the material structure. Owing to a few limitations associated with NDT methods toward dielectric materials, microwave-based testing such as microwave non-destructive testing (MNDT) appears to be recognized and preferred for penetrating the dielectric material. The method, which implies employing high-frequency energy ranging from 300 MHz to 300 GHz, could extract the dielectric properties of permittivity and permeability, which will be important in characterizing dielectric materials. In this paper, the four categories of resonator method, resonant perturbation method, reflection method, and transmission-reflection method within each measurement system have been reviewed. Each of the measurement methods serves particular principles and applications with respect to its frequency range, benefits, constraints, type of material tested, and accuracy. Based on the research findings, these methods have contributed to various fields of dielectric material characterization (solids, liquids, and gases), inspection of layered composites, surface crack detection, biological application, and also sensors design.**

***Index Terms*—Dielectric material, Microwave non-destructive testing (MNDT), Non-destructive testing (NDT), Permeability, Permittivity, Reflection, Resonator, Resonant perturbation, Transmission-reflection.**

I. INTRODUCTION

THROUGHOUT the years, NDT has been developed every now and then to ease the process of evaluating material properties and inspecting defects in a wide realm of applications. NDT refers to an array of inspection and evaluating methods used in the science and technology industry to assess certain materials, components, or systems in comparison to particular criteria without modifying the entire properties and damaging the material being tested [1]. There are numerous non-destructive techniques and methods available [2]. These techniques can be used on metals, ceramics, composites, coatings, and many more materials to detect flaws, defects, or any other quantitative measurement properties of an object.

On the other hand, despite the wide-ranging application of NDT, these techniques are limited in terms of dielectric material penetration capabilities. A dielectric material is an electrical insulator that can be polarized by an applied electric field which is classified into two types, capacitor dielectric materials and microwave dielectric materials [3]. Dielectric materials are promising for microwave absorption applications due to their low density, high aspect ratio, fine anti-oxidation capability, and ability to be assembled into macroscopic architectures or films [4]. Thus, one of the alternatives for evaluating dielectric materials is known as microwave-based testing.

In microwave-based testing, dielectric material inspection is a main application area for Microwave Non-Destructive Testing (MNDT).The American Society for Non-destructive Testing (ASNT) officially acknowledged and designated microwave non-destructive testing as a 'method' by itself. MNDT comprehend to imply using high-frequency electromagnetic (EM) energy (frequency range spans approximately from 300 MHz to 300 GHz) to inspect and characterize materials [5]. The microwave technique is particularly ideal for the penetration and inspection of these dielectric materials, and it can also be used for examining surface breaking defects in conductive materials [6–8]. To name a few application areas, these techniques are well suited for materials characterization, layered composite inspection for thickness, disbond, delamination and corrosion under coatings, surface-breaking crack detection and evaluation, and cure-state monitoring in concrete and resin-rich composites [6].

Microwave-based testing, as well as MNDT, has shown its significant towards various non-metallic materials such as concrete, composites, non-metallic pipes, rocks, ceramic, coating, etc. based on the different types of applications [9–15]. Microwave signals propagate in the air and penetrate inside dielectric media easily with low attenuation [9]. As MNDT is notable as a contactless feature, low operating power, and good non-metallic content penetrability, it is also beneficial in terms of cost. Performing measurements using microwave laboratory test equipment literally requires a high budget. Hardware for a specific application, on the other hand, can be conceived to be relatively inexpensive due to the rising availability of low-cost

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highly integrated microwave components. It also can be built with basic in design, hand-held, battery-powered, operator-friendly, and function on an on-line basis. Contrary to the earlier years, microwave equipments are high-priced and complex, restricting the widespread application of microwave technologies [10]. It also reduces production time and energy usage as reported in the manufacture of high-performance cement paste [11]. Consequent to these advantageous and other features that are not stated, MNDT has received quite of interest with the potential to overcome the limits of both conventional testing and NDT especially towards the dielectric materials and non-metallic materials.

On a macroscopic scale, microscopic interactions can be grouped into what are known as dielectric material properties, which include the material's ability to retain or absorb microwave radiation. These properties influence how an EM wave interacts with a material, such as reflection, refraction, attenuation, and many more [7]. Hence, the measurement of dielectric properties plays an important role in characterizing and evaluating dielectric materials. Measuring the dielectric properties of materials involves the measurements of the complex relative permittivity, ε_r and complex relative permeability, μ_r. According to the transmission line theory, the complex permeability and permittivity are two important factors to determine the microwave absorption abilities of the EM wave absorbing materials [16].

Permittivity refers to a measure of a material’s capability to resist an electric field, while permeability is a measure of a material’s capability to support the formation of a magnetic field within itself in response to an applied magnetic field [17]. A complex permittivity is defined as (ε'-jε'') with an EM field where ε', is a real part and ε'', is an imaginary part. The real part of the complex permittivity is known as dielectric constant, is a measure of the amount of energy from an external field stored in the material. Meanwhile, the imaginary part of the complex permittivity is identified as the loss factor, a measure of the loss of energy in a dielectric material through conduction, polarization, and other dissipative phenomena. The loss tangent, tan δ represents a ratio of the imaginary part to the real part of the complex permittivity. The loss tangent is called as dissipation factor which is often used interchangeably with the term power factor, PF. A material is considered as a good dielectric when the energy stored per cycle is higher than energy loss per cycle or in other words, the lower the loss tangent of a material, the lower the attenuation when the wave propagates through the material as expressed in the equation (1) [18].

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\text{energy loss per cycle}}{\text{energy stored per cycle}} \tag{1}$$

Permeability, μ describes the interaction of a material with a magnetic field. The response of a material to EM fields is determined by the displacement of free and bonded electrons by electric fields, as well as the orientation of the atomic moment by magnetic fields [19]. The complex permeability also consists of a real part and an imaginary part whereas the real part, μ' represents the material storage capacity of the magnetic field. As for the imaginary part, μ'' , it represents the amount of energy dissipated due to the magnetic field. Measurement of the complex permeability is only applicable to magnetic materials, thus the permeability of non-magnetic materials is as almost as the permeability of free space, which is equal to one. A material with a good magnetic permeability has lower attenuations and magnetic loss where potential energy in the magnetic field should be greater than dissipated energy. The energy loss in the magnetic field is defined as magnetic loss tangent and is expressed as (2) [20]:

$$\tan\delta_m = \frac{\mu''}{\mu'} = \frac{\text{energy loss per cycle}}{\text{energy stored per cycle}} \tag{2}$$

There has recently been a surge of interest in determining the dielectric properties of materials at microwave frequencies. This is due to the importance of dielectric properties in the construction of high-frequency electronic components, superconducting material properties, printed circuit board (PCB) substrate quality, microwave absorption material efficiency, metamaterial characterizations, and dielectric antenna design performance [21]. Many techniques have been designed for measuring complex permittivity and permeability at microwave frequencies. According to microwave theory, material characterization can be classified into two categories, non-resonant methods and resonant methods, each with its own set of constraints that limit it to specific frequencies, materials, and applications [21–23]. There is no single technique that can characterize all materials over the entire frequency band for dielectric measurements. When characterizing materials, there is always uncertainty in dielectric measurements, dependind on some significant factors of accuracy, frequency, temperature, material nature, material geometry, thickness, dielectric loss, and so on. It is favorable to use more than one method of measurement to fully characterize the EM properties of a material in a precise and accurate manner [23].

This research will review some of the various dielectric material measurement methods (resonant and non-resonant) that have been applied in microwave fields. In the resonant method section, it will consist of the resonator method (dielectric resonator, split-cylinder resonator, and open resonator) and the resonant perturbation method (cavity perturbation and wall-replacement), while in non-resonant method section will cover the reflection method (open-ended coaxial and waveguide probe) and transmission-reflection method (free space and transmission line).

II. DIELECTIC MATERIAL MEASUREMENT TECHNIQUES

Dielectric measuring method can be broadly classified into two types namely resonant and non-resonant. The resonant method is based on measuring the resonance frequency and quality factor, whereas the non-resonant method is based on measuring the transmission and reflection of the EM wave travelling through the material being tested. The resonant methods provide good accuracy at single and discrete frequencies, while the non-resonant methods offer simple and less sample preparation throughout a wide frequency range [24-25].

A. Resonant Method

Resonant methods offer relatively precise parameter extraction, especially for low dielectric loss materials. They are more beneficial in terms of accuracy and sensitivity compared to non-resonant methods given that the material properties are only required across a narrow frequency band [24-25]. They generally can be classified into two main approaches, which are the resonator method, and resonant perturbation method.

1) Resonator

In resonator methods, the material under test (MUT) is excited as a part of the resonator structure in the measurement circuit, and its dielectric properties are deduced from its resonant properties [23-25]. Resonators implemented on dielectric materials must be designed based on its measured material and frequency. Based on dispersion theory, the wavelength and wavenumber of a wave are proportional to its frequency, thus the dielectric material properties of permittivity and permeability can be extracted from the measurements of shifting resonance frequency, f and quality factor, Q of a dielectric resonator for a given dimension [22-26].

a) Dielectric Resonator (Hakki-Coleman Method)

One of the earliest measurement methods used as dielectric resonators is known as Hakki-Coleman method. The Hakki-Coleman proposed the technique of measuring the dielectric and magnetic properties of a homogenous isotropic medium at a frequency range of 1 to 30 GHz. A cylindrical dielectric resonator rod is placed between two parallel mathematically infinite conducting plates as shown in (Fig. 1). The dielectric properties of relative permittivity are determined by the resonant frequency, resonator dimension, and unloaded Q value. The Hakki-Coleman method reported that the dielectric constant of Teflon, polystyrene, and lucite is measured with an accuracy lower than ±0.2 % [27-28]. This Hakki-Coleman method was later improved to span a wide range of frequencies since coaxial lines do not have the cut-off frequency and to improve the accuracy of loss tangent measurement that occurred due to conductor losses and radiation effects [27–30].

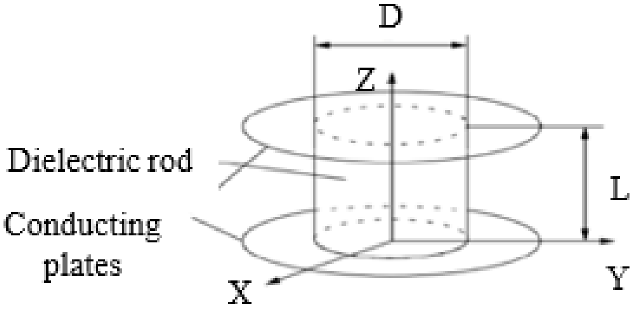


Fig. 1.Configuration of a dielectric rod resonator short circuited at both ends by two parallel conducting plates. Reprinted from [31].

b) Split-Cylinder Resonator

The split-cylinder resonator method required no sample machining, simple measuring procedure and operated at a frequency range of 10 to 60 GHz. This method is published by Kent [32-33] as non-destructive method and later a model that improved the accuracy of relative permittivity, accuracy of loss tangent and broadband measurements is developed. The developed model represents the accurate fringing fields and the derivation of resonance condition the modal analysis without introducing a systematic error in the calculation of the tested materials relative permittivity [34]. The split-cylinder resonator consists of two air-filled cylindrical resonant cavity, where a planar dielectric sample is placed in the gap between the two sections [32–35], as shown in Fig. 2. A cylinder half is fixed, and another half is adjustable allowing the gap to accommodate varying sample thicknesses. Two coupling loops in both waveguide sections are connected to the input ports of a network analyzer via coaxial transmission lines to excite the transverse electric (TE) modes of the resonator. This will result in the orientation of electric field tangential to the MUT surface, making the electrical resistance field generated at the end of the flux in material has no significant effect.

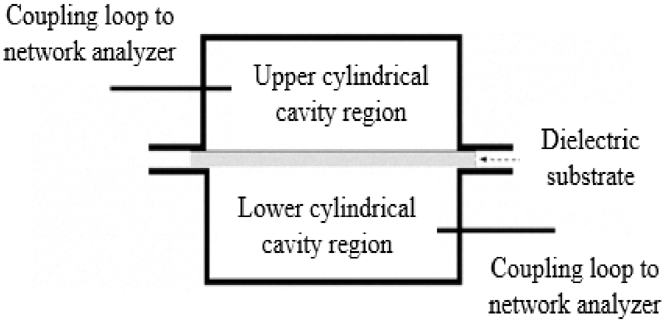


Fig. 2. Cross section of split-cylinder resonator. Reprinted from [36].

c) Fabry-Perot Open Resonator

The Fabry-Perot type open resonator offers the highest available accuracy for measurements of real permittivity and loss tangent of ultra-low loss dielectric materials and also in broadband operation [37-40]. This method possess a number of additional properties which enhance their utility in determining complex permittivity of materials in 20-100 GHz frequency range [37-38]. One of the main features is that open resonator has no side walls, make the irregular losses from the walls are negligible, thus increased the possibility of obtaining high Q-factor at the high frequency regions. The most widely used approximation method for determining complex resonance frequencies of Fabry-Perot open resonator is based on a characteristic equation derived under the assumption of Gaussian type modes distributed between spherical mirrors separated by a given distance (Fig. 3) [38-39, 41]. In this circumstance, the resonant frequency shift caused by the presence of the film and its thickness must be measured. The advantage of this spherical resonator is that it does not require the dielectric characteristics of the substrate, and the accuracy can be improved. Instead, the thickness of the film must be known, and only discrete measurement frequency points can be chosen.

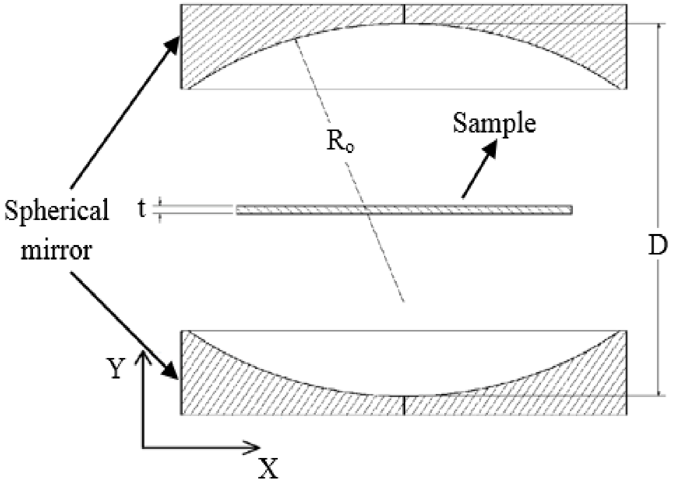


Fig. 3. Cross-section of Fabry-Perot resonator. Reprinted from [41].

2) Resonant Perturbation

In resonant perturbation methods, the MUT is introduced to a resonator, causing the dielectric boundaries of the resonator to change, and the dielectric properties of the material are deduced from the change in the resonant properties of the differential measurement between the empty and a material-filled resonator [42]. The method is frequently utilized for low-loss samples, powders, small-size samples, and irregular-shaped samples owing to its favorable accuracy and flexibility in sample preparation. Bethe and Schwinger originated the theory of cavity perturbation where the possibility of perturbation was considered based on two scenarios: first, a small dielectric sample is put into the cavity, and second, a minor deformation on the cavity's boundary surface [43]. In other words, resonant perturbation method involves cavity perturbation method and wall replacement method.

a) Cavity Perturbation

After years of development, cavity perturbation method has gained recognition because of its accuracy, simplicity, noncontact feature and is now utilized by multiple researchers to measure the complex dielectric properties of dielectric materials at microwave frequencies [43-46]. The cavity perturbation methods are widely used in the study of the dielectric properties of biological material, catalyst material, common plastics and many more [43-45]. In cavity perturbation methods, when an appropriately shaped MUT is inserted into the cavity, the electric field in the cavity will be disturbed, causing the resonant frequency and quality factor of the cavity to change. The dielectric properties of the MUT can be measured using the perturbation theory and formula if the parameters of the cavity and the disturbed cavity are known, because the resonance behavior of the cavity is determined by the dielectric properties of the material distribution inside [46].

b) Wall Replacement

The wall replacement method often applied in electrodynamic properties of conductors and has developed a lot of methods in surface resistance measurement of superconducting thin films, superconductors, metal and conducting coatings [47-49]. The surface resistance is the physical quantity of interest for the study of dissipation phenomena of materials engaged in microwave applications. In wall replacement methods, part of the resonator wall is replaced by MUT surfaces. Surface resistance testing with typical cavities may require the use of very high frequencies or very large surfaces [47], though the use of low-loss, high-permittivity dielectrics to load the resonator allows for the measurement of smaller samples at microwave frequencies. The surface resistance is determined by calculating the changes in quality factor (Q) obtained in a resonator when a part of the resonator base is replaced with MUT [47-48].

B. Non-resonant Method

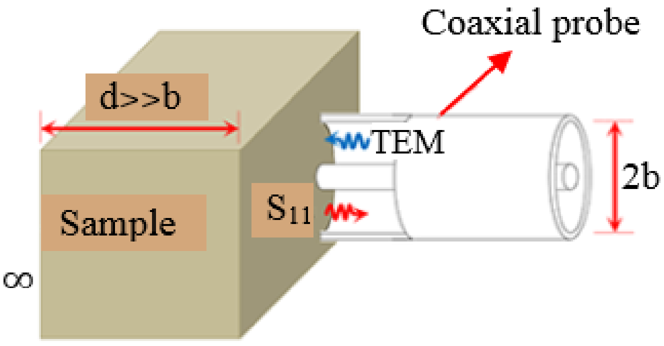
At the interface between the two materials, partial reflection of EM waves occurs as a result of changes in impedance and wave velocity. A non-resonant method characterizes the material by evaluating the reflection and transmission data in form of scattering parameters (S-parameters) that obtained through a vector network analyzer (VNA) when EM wave travels through a medium [22, 50]. Non-resonant methods are further subdivided into two types [6, 22], reflection method where only the reflection data is needed and transmission/reflection method where both the reflection and transmission data are required to determine the dielectric properties of material.

1) Reflection

In reflection method, the transmitted or refracted signal across the medium does not need to be measured since the method is based on reflection from the material [22-23]. This method can generally only measure a single parameter, either permittivity or permeability. Thus, in order to calculate both complex permittivity and permeability at simultaneous time, two or multiple independent reflection measurements are required [21, 51]. In the category of reflection-based, two of the common methods are open-ended coaxial probes and open ended waveguide probes, whereas in both circumstances, the probe is positioned against the surface of the MUT, or with a standoff between the probe and the MUT [6].

a) Open-Ended Coaxial Probe

Open-ended coaxial probe measurement system typically consists of a vector network analyzer, software, coaxial probe, probe stand and cables. A reflection method by means of the reflection coefficient measurement on the interface between two materials with different impedances, on the open end of the coaxial line (as a detector) and the MUT while propagating over the coaxial line. The method that most commonly used for dielectric properties of biological tissues offer a few advantageous features such as non-destructive, simple implementation, minimum sample handling, and operate at broad frequency range [52-55]. This method converts changes in the dielectric properties of material from the phase and magnitude of the reflected signal at the end of the open-ended coaxial probe into reflection coefficient [53]. A typical coaxial cable is made up of two conductors separated by a dielectric insulator (Fig. 4) Transverse electromagnetic (TEM) mode is the single mode of transmission permitted within the dielectric material in such cables. As a result, the electric and magnetic properties of an incident wave are only present in the plane perpendicular to the propagation direction [54-55].



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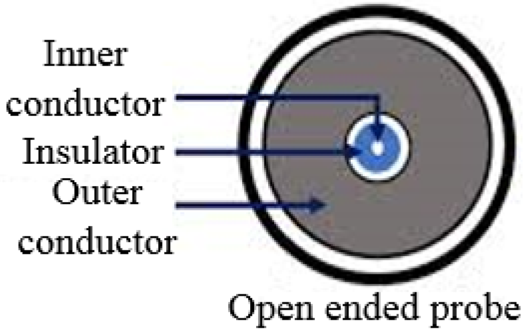

b)

Fig. 4. a) Open-ended coaxial probe measurement. b) Cross-section schematic of the probe. Reprinted from [21], [50].

b) Open-Ended Waveguide Probe

The open-ended waveguide probe is a common non-destructive method for solid materials characterization and inspection of multi-layered structures [6], [57-58]. This method efficiently emits energy into the structure, allowing penetration into thicker and higher loss structures due to field confinement, and its ability to control the polarization of the applied electric field [59]. The MUT should be planar, or at least locally planar, and can have an indefinite number of layers. As this approach only includes a reflection measurement, the MUT does not need to be cut or molded to fit inside a certain geometry, instead, just one side of the sample must be accessible. Open-ended waveguide probe operates similarly to coaxial probe except that instead of propagating TEM modes, the waveguide can only propagate TE and transverse magnetic (TM) modes due to having just a single conductor (Fig. 5) [6], [60]. The sample is considered infinite, as long as the sample thickness is greater than the radius of the outer conductor. The magnitude of the S-parameters is determined by the geometrical and electrical characteristics of the irradiated material as well as the probe that emits EM waves. The S-parameters acquired from the VNA represent the magnitude of the signal reflected back at the aperture of the probes in relation to the transmitted signal that will later transformed into complex dielectric permittivity through some calculations [21].

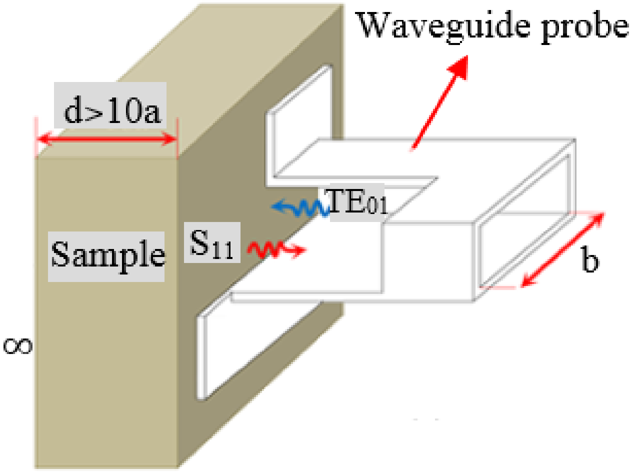

Fig. 5. Rectangular waveguide open-port measurement. Reprinted from [21].

2) Transmission-Reflection

Measurement in the transmission-reflection method is based on reflection from the material and transmission through the material. In this approach, the EM waves must be directed towards the material before collecting the reflected energy from and through the material [22]. In contrast to the reflection method, this type of measurement method such as free space and transmission line can provide both relative permittivity and permeability as well as other properties of the material as both the reflected and transmitted waves are strongly dependent on the dielectric and magnetic properties of the MUT and its thickness [6], [23], [26], [61]. In general, the transmission-reflection method involves three main steps of calibrating the S-parameters measurement equipment, measuring the material S-parameters, and estimating the dielectric material properties based on the measured S-parameters using EM theory [62].

a) Free-Space

Free space measurement provides the fewest limitations on material geometry and has the advantages of being non-destructive in evaluating material without prior machining and physical contact at high frequencies [61–63]. Thus, it is ideally suited for evaluating the performance of microwave absorbing materials throughout its design and development phases in the lab, as well as during its practical use in the field [61]. This method has been widely implemented in high-temperature environments since the horn radiators or antennas are contactless with MUT, preventing heat damage to the measuring equipment [6, 21]. It has also been used to characterize huge flat solids, liquids, gases, radomes in aircraft, multi-layered dielectric materials, composite materials, and metamaterials [61], [64]. The free space measurement setup system consists of the VNA, two lens horn antennas that are linked to the VNA, and a holder that holds the material between two antennas (Fig. 6) [65].

In the case of free-space measurements, VNA emits an EM signal through its transmission port (port 1), illuminating the MUT with microwaves. The signal is partially reflected back to the transmission port and partially sent to the receiving port (port 2). VNA distinguishes these waves with couplers or bridges and measures the phase and magnitude of each wave to analyze the behavior with its four S-parameters of S_{11}, S_{12}, S_{21}, and S_{22} [61], [64]. The real and imaginary parts of complex permittivity and permeability can be derived from the following S-parameters using different conversion approaches such as Nicholson-Ross Weir (NRW), NIST iterative, new non-iterative, and short circuit line (SCL) [66-67].

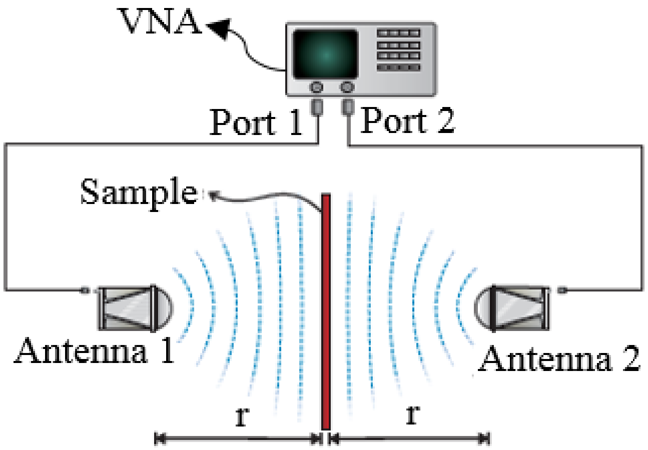

Fig. 6. Transmission and reflection of two-port free-space measurement method. Reprinted from [64].

As the measurement does not limit on the material geometry, it has been used to investigate the S-parameters of the edible oil using X-band frequencye (8 GHz to 12 GHz), where the sample measured is placed in the acrylic sample holder and put in between the shared focal plane of the transmitter and receiver lenses [68]. The measured radiation patterns obtained by the VNA can be used to compute the 3 dB and 10 dB E-plane beam widths. Beam widths shift proportionally to wavelength in free space. Due to the spot focusing action of antennas at the focus, diffraction effects are minor if the minimum transverse dimension of the sample is three times the 3dB E-plane beam width. We also using the same measurement system and procedures to carry an ongoing study in investigating the S-parameters and the dielectric properties of sludge waste from waster treatment. The study is to determine the sludge waste can be safely reused for other purposes, for instance whether the sludge waste might imitate the soil behavior that is suitable for plant growth or can be used as fertilizer.

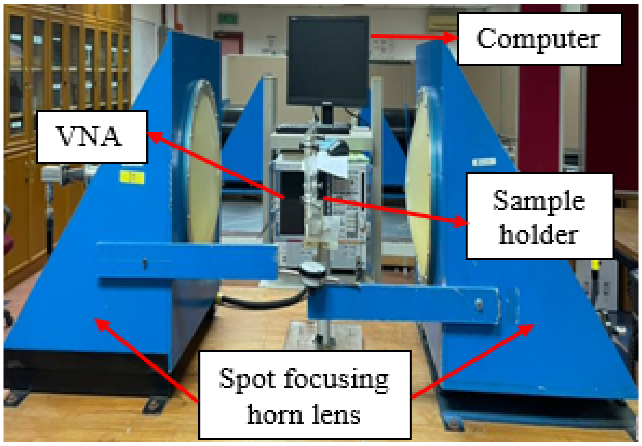

Fig. 7. MNDT free space measurement set up.

b) Coaxial Transmission Line

The transmission line method advocates inserting the material into a section of an enclosed transmission line, which is typically a section of waveguide or coaxial line. In same category of measurement with free-space, transmission line method permit a two-port transmission analysis of the material, which allows the complex form of both the permittivity and permeability to be determined [69]. For a wide range of materials with dielectric loss and frequencies, the transmission line enables a measurement with minimal random error because there are many calibration methods available to minimize systematic errors of intermediate transmission lines between network analyzer ports and the MUT [70-71].Compared to both waveguide and coaxial transmission line, coaxial structure covers a higher range of frequency and a larger sample volume [72-73]. Many microwave circuit components have been identified to be easily fabricated using coaxial structures. Filters, for example, can be created with higher Q-factors employing coaxial transmission lines instead of planar structures such as microstrip-based systems [74].

A VNA, a coaxial air-line, and an external computer are involved in a coaxial transmission line measuring system (Fig. 7). EM waves are directed to the MUT, which is located within the closed portion of the coaxial line connected to the VNA, allowing the extraction of four S-parameters (S_{11}, S_{12}, S_{21}, and S_{22}) that determine the reflection signal (port 1) and transmission signal (port 2) of the MUT [72], [75]. The materials should be tightly fitted into the structure for precise dielectric measurement [73]. The coaxial transmission guide generates a TEM wave between the coaxial line's inner and outer conductors, where the electric and magnetic field components are perpendicular to the propagation vector [76]. The obtained S-Parameters from the de-embedding process are used to evaluate the complex permittivity and permeability of the material by knowing the intrinsic dielectric properties and taking dielectric loss into account [77].

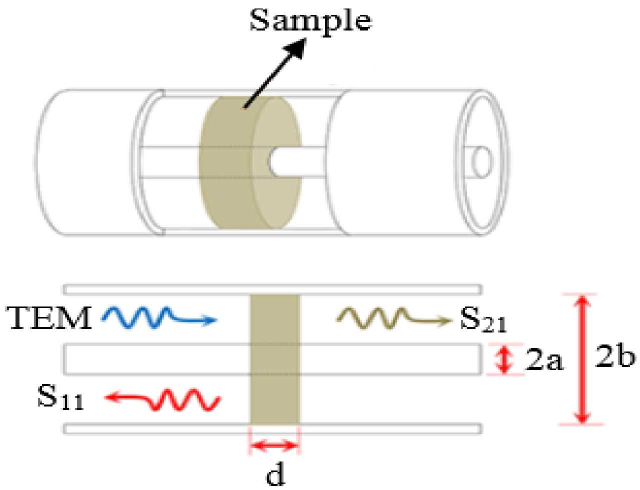

Fig. 6. Two-port measurement using coaxial transmission line. Reprinted from [21].

III. FINDINGS

METHODS / FREQUENCY RANGE	FINDINGS	LIMITATIONS	REFERENCES
Dielectric resonator (Hakki-Coleman) 1 GHz - 30 GHz	●Provides an accuracy lower than 0.2% when measuring relative permittivity ●Sensitive in measuring very low loss tangents materials	●Required an accurate machining ●Better suited for higher relative permittivity materials ●Conductor losses and radiation effects of loss tangent measurement	[27–31]
Split-cylinder resonator 1 GHz - 10 GHz	●Less interaction with cavity walls (non-destructive) ●Sample machining is not necessary ●Possible of characterizing thin materials ●The frequency shifts is generally small	●The modelling is complicated and has no analytical models ●Restriction over the material thickness ●Frequency decoupling issues at higher frequencies (above 10 GHz)	[32–36]
Open resonator (Fabry-Perot) 20 GHz – 100 GHz	●Simple machining (easy insertion and removal of material tested) ●Irregular losses from the walls is negligible since there is no side walls ●Could obtained high quality factors of its resonances ●Sensitive to any kind of loss related to radiation	●Diffraction at the edge of mirrors/lenses caused the energy losses ●Not suitable for measurement of thin materials ●Coupling effects of Gaussian modes of interest with higher order modes (affects the resonance frequency of the resonator loaded with the material tested)	[37–41]
Cavity perturbation 1 GHz – 50 GHz	●Accurate for measuring small size samples (volume of the sample is smaller than the volume of the cavity) ●No severe tolerance limit on the shape and dimension of material tested ●The calculations for the complex permittivity is simple (does not require the computer program)	●The material presence in the cavity could decrease the quality of the cavity due to the presence of sample's dielectric loss ●Not suitable when measuring large sample size (accuracy decreased) ●Not suitable for high loss materials	[43–46]
Open-ended coaxial probe / Open-ended waveguide probe 0.1 GHz – 100 GHz/ 500 MHz – 60 GHz	●Easy sample handling ●Can be used in a temperature-controlled environment ●Simple fabrication ●Operate efficiently over a standard waveguide bands up to the terahertz region ●Confine the radiated fields (allowing penetration into thicker and higher loss structures)	●Air bubbles and uneven sample surfaces could lead to inaccuracy (air gap effects) ●Essentially reserved only for permittivity measurement of non-magnetic materials.	[6], [21], [52—60]
Free space 1 GHz – 170 GHz	●Can be used in high-temperature environments ●Contactless measurement ●Can evaluate both permittivity and permeability properties	●Material tested need to be in a large size and flat surface ●Diffraction effects at the edges of the material tested ●Multiple reflections between the material surface and the antenna could lead to some errors	[6], [21], [61–68]
Coaxial transmission line 1 GHz – 100 GHz	●Commonly measure materials with medium to high loss ●Can evaluate both dielectric and magnetic properties of the material ●Cover a higher frequency range and larger volume than waveguide transmission line ●Microwave circuit components are easy to be fabricated	●Air gap effects could limit the measurement accuracy ●Low accuracy when the sample length is the multiple of one-half wavelength in the material	[70–77]

IV. CONCLUSION

The field of microwave-based testing and MNDT has broad applicability especially in penetrating dielectric materials. The study on dielectric material measurement methods is such an important work towards optimizing the performance of determining and evaluating dielectric material properties of complex permittivity and permeability. In this study, the methods of dielectric resonator, split-cylinder resonator, Fabry-Perot open resonator, cavity perturbation, wall replacement, open-ended coaxial probe, open-ended waveguide probe, free space, and coaxial transmission line have been comprehensively reviewed within each measurement system and category. These methods have been contributing in areas of dielectric material characterization, inspection of layered composites, surface crack detection, biological application, sensors design, and it is expected to show more practical utilization in future especially for high-frequency applications. However, each system with a set of measurement parameters typically optimized with its own uncertainty that limited to a specific environment, frequency, type of material, accuracy, and application. For the same system to be used in another occasion, certain adjustments may be required and for some circumstances, combining the dielectric measurement method with another NDT or MNDT method is deemed as feasible solution in extracting the EM properties. As the microwave testing and MNDT is widely applicable for inorganic materials, further study and research should be consider utilizing these methods towards more organic materials in laboratory investigations and also in practical applications. Such work will contribute significantly in conserving natural resources by fulfilling the demands for reusing and recycling organic material for other applications.

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