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A Brief Review of Measuring Techniques for Characterization of Dielectric Materials

[1]Muhammad Taha Jilani, Muhammad Zaka ur Rehman, Abid Muhammad Khan, Muhammad Talha Khan, Syed Muzamil Ali

Department of Electrical & Electronics Engineering, Universiti Teknologi PETRONAS, Malaysia
E-mail: [1]taha.foru@gmail.com

ABSTRACT

The Dielectric property of material has gain significance in industrial application in recent decade. These properties provide useful information to improve the design, processing, quality and control of product. Among various techniques, to opt an appropriate method it is required to consider various factors. In this paper main characteristic of these properties followed by brief introduction of measuring technique is presented. In later part, a comparative analysis of important techniques is outlined.

Keywords: *Dielectric measuring techniques, dielectric spectroscopy, characterization of materials*

1. INTRODUCTION

Dielectrics are the poor electric conductors (non-ideal insulator), most of the materials including living organisms and most agricultural products can conduct electric currents to some degree, but are still classified as dielectrics. Electrical characteristics of every material are different to each other which are dependent on its dielectric properties. These properties provides the valuable information which helps researchers and engineers to utilize these data into their design or for the purpose of material characterization or for monitoring process quality [1].

For the dielectric properties the main parameter is the complex permittivity (εr*) which describes the material behavior when it is subjected to an electromagnetic field. A material which has the ability to store energy when an external electric field is applied can classified as “dielectric”. Complex permittivity (or complex relative permittivity) is defined by [2]:

$$\varepsilon^* \text{ or } \varepsilon_r = \varepsilon_r' - j \cdot \varepsilon_r'' \qquad (1)$$

In above equation, j = −1, εr′ is real part called dielectric constant (εr′) or dielectric permittivity which represents the storage of electric field and εr″ is an imaginary part, called loss factor which represents how much energy dissipate is a measure i.e. how dissipative or lossy a material is to an external electric field. Conductivity (σ) measures the ability of material's to conduct an electric current [3, 4]. The dielectric constant is associated to material’s capacitance which is ability to store energy (polarization) i.e. how much electrical energy store when an electric field is applied [5].

The ratio between dielectric constant (real part) and loss factor (imaginary part) of permittivity correspond to another parameter, dissipation factor or loss tangent.

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (2)$$

tanδ represent ratio of energy lost to energy stored per cycle as defined by [6].

2. TECHNIQUES FOR DIELECTRIC MEASUREMENTS

For the dielectric measurement no single technique can characterize the all materials over entire frequency band. A measurement with accuracy for both types (lossy and low-loss) of material is challenging so each band and their losses require a different method. There is always uncertainty in dielectric measurements while characterizing the materials [7]. Some significant factors on they depend are

- Frequency
- Required accuracy
- Temperature
- Material nature
- Sample size/thickness
- Contacting/Non-contacting
- Destructive/Non-destructive
- Cost

In view of aforementioned factors we can conclude while selecting the appropriate measuring technique; testing frequency and the type of test material should be considered. Even the selection of measurement equipment, the sample holder and its design are based on frequency and the material. As concern to measuring techniques, they can broadly divide into two main categories namely, resonant and non-resonant, the resonant methods can characterize the material at single or with some discreet frequency points. In this method a dielectric material used as a resonant element but it limited only for low loss test samples, some examples are; dielectric, planar and split resonators methods. Other method is perturbation method, in which a sample is placed into a resonant cavity that causes the perturbation, resulting resonant frequency shift [8]. This method is suitable for lower and moderate-loss samples.

A non-resonant method can measure over the broad range of frequencies. It can categorize the material by determining the reflection and transmission coefficients that causes bychanges in characteristics impedance and wave velocity [9]. Among various techniques some most popular and most important methods for dielectric measurements are briefly discussed here:

- **Coaxial Probe Method:** This is the one of the most convenient and frequently used technique to measure lossy materials at high frequencies (i.e RF and microwave) commonly it is known as coaxial probe or coaxial-line probe or an open ended coaxial-line method [3]. It is used with VNA, that measures complex reflection coefficient.

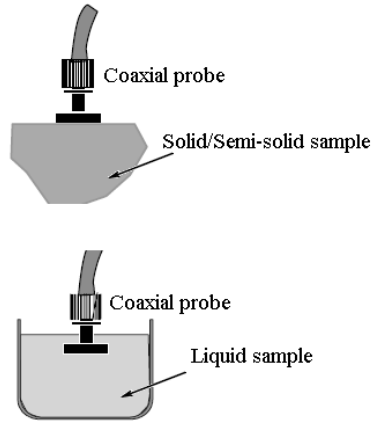

Figure 1: Coaxial Probe Method [4]

Coaxial line uses a metallic probe which senses reflected signal (phase and magnitude) from the MUT. For flat surfaces probe touches sample and for liquids it immersed into sample. It is quite simple method and its make possible to carryout dielectric measurements over broad frequency range around 0.5GHz to 110 GHz. But this method shows some deflection for the low permittivity materials [10] measurements over broad frequency range around 0.5GHz to 110 GHz. But this method shows some deflection for the low permittivity materials [10].

- **Transmission Line Method (Waveguide):** It is another common method in which a material sample is put inside the center of enclosed transmission line (as shown in Fig-2). For measurements reflection and transmission both coefficients are used. It has higher accuracy and more sensitivity than the coaxial line but relatively it has a narrower frequency range than coax [10]. Sample preparation relatively difficult thus more time consuming because sample must cover entire cross-section area of a line, therefore it must be in slab or annular geometry form [8].

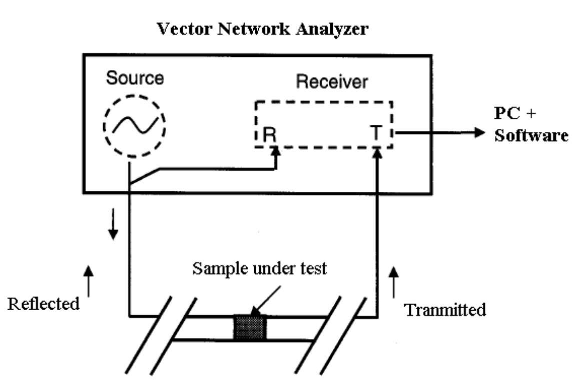

Figure 2: Transmission Line (Waveguide) Method [8]

- **Free Space Method:** This technique is non-contacting and nondestructive, typically use at higher frequency, although it can be use with low frequency but it has practical sample size limitation. In Free-space method the large, flat and both side proper-faced samples of homogeneous (uniform without irregularities) solid materials are use to measure the dielectric characteristics. Material placed between two horn-antennas to directed energy on or through it in conjunction with vector network analyzer [11]. The advantage of using free-space measurement technique is to get reflection and transmission coefficients while no physical contact to sample, which is best for thin flat materials [12].

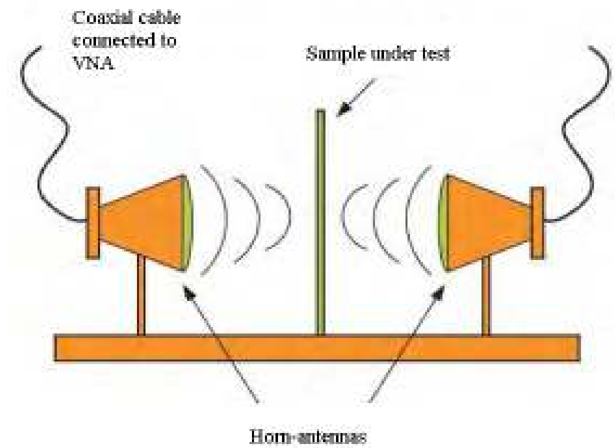

Figure 3: Free Space Method [9]

- **Resonant Cavity Method:** This technique is typically used for dielectric measurement of homogeneous materials due to its simplicity with higher accuracy and high temperature measurement support, also for low dielectric loss materials and low loss-factor it gives accurate results [10]. It is designed in either TM (transverse magnetic) or TE (transverse electric) propagation mode. This method is based on a fact that, shift in resonant frequency of a tuned cavity, caused by insertion of a lossy material into it. Sample is place in center of the waveguide, either circular or rectangular, resulting it changes in the center resonant frequency and quality factor, which gives the information of the inserted sample to calculate the dielectric constant. [8]. A piece of sample effects not only the center frequency but also quality factor (ratio of energy stored to energy dissipated) of the cavity. From these parameters, the complex permittivity (εr) or permeability (μr) of the sample can be calculated at a single frequency [4]. The typical measurement range for this method is 50MHz to more than100GHz. For each cavity it needs calibration prior to measurement, but once it calibrated, further measurements are rapid. Compare to other techniques the sample preparation is easy and rapid, within short time-period one can measure large number of samples. Measurements can be taken over high temperatures to low temperatures (140°C to −20°C) [10].

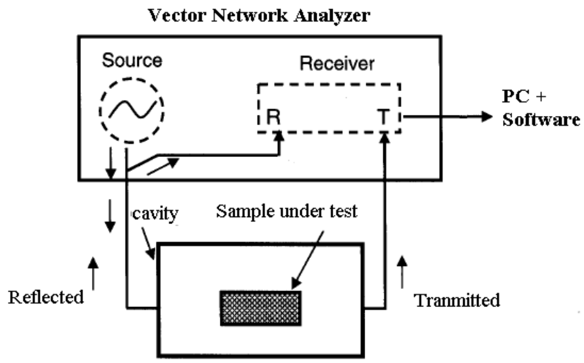

Figure 4: Cavity Resonator Method [8]

- **Parallel Plate (Electrode) Method:** The parallel plate capacitor method is involves sandwiching of a dielectric material (thin sheet sample) between two electrodes to form a capacitor. Measurements can be taken using LCR meter or impedance analyzer and a dielectric fixture [4], see Fig 5. In this method typically low frequencies (< 1 GHz) are used. Parallel plate test parameters are derived by considering the dimensions of the material and by measuring its capacitance and dissipation factor. To measure dielectric constant, placing a dielectric sample into a sample holder; then use capacitance value to calculate the permittivity. It has high measurement accuracy (about ±1% for εr' and 5% ± 0.005 for tan δ) and involves very simple sample preparation and setup, typically frequency range from 20 Hz to 1 GHz use for this purpose. However, air gap and its effects can cause significant error if not considered and calibrated [11]. Also due to electrode polarization effect, spurious measurements lead to poor result. It can be mitigate by using electrodes with large microscopic surface or by using higher frequencies; as the effect is reduces rapidly with increasing frequency [3].

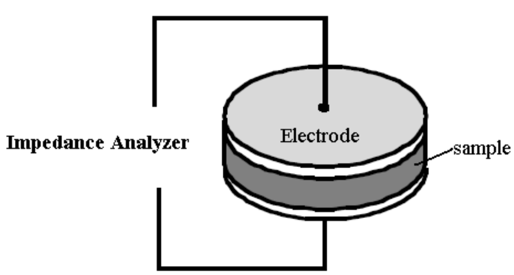

Figure 5: Parallel Plate (Electrode) Method

- **Planar Transmission Line Method:** These types of transmission lines are widely using in various RF & microwave components, microstrip line is the most common and simple technique for characterizing the dielectric materials. It's easy to fabricate, with low manufacturing cost while compactness of structure make it more suitable for industrial applications. The test sample can be used either as substrate (in case of solid) or superstrate (for both, solid and liquid) for dielectric permittivity measurements [9]. It is well know that the effective permittivity of MSL will change when a dielectric sample placed over the quasi-TEM transmission line, which is highly dependent on permittivity of sample. To take measurement, effective dielectric constant determine in un-loaded condition after that the sample placed on the signal strip (as shown in Fig.6), this will change the effective dielectric constant (εeff) and characteristic impedance (Z0) of MSL, which can be used to extract the dielectric properties of sample. In [13] Bernard uses microstrip ring resonator for dielectric measurement, a sample placed on top of ring that changes the resonant frequency by modifying the substrate or air-boundary, this method shows a noticeable shift in the resonant frequency and the change in the quality factor. The effect of dielectric sample is more prominent when using it as substrate rather as overlay test material.

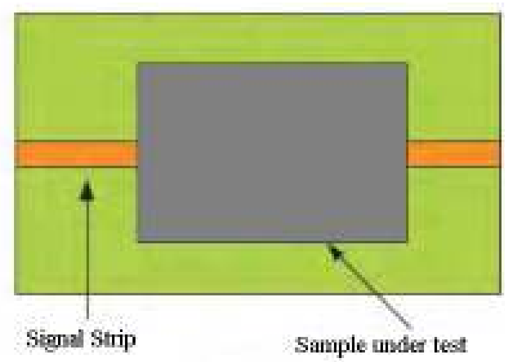

Figure 6: Planar Transmission Line
(Top View of MSL) [9]

3. COMPARATIVE ANALYSIS FOR DIELECTRIC MEASURING TECHNIQUES

As we discussed before the selection of dielectric measuring technique is basically depended onto several factors, this selection is associated to the test material. Electrical characteristics of every material are different to each other which are dependent on its dielectric properties. And this dielectric behavior of material can be varying with testing frequency, temperature, sample size etc. The dielectric constant is dependent on frequency; as frequency increases it decreases, so if we measure a material at lower frequency its dielectric constant will change from high frequency measured value. In [14] Zajíček measured a biological tissue at low frequency which give ε'r ~200 and for the same sample with high frequency measurement it gives ε'r ~ 50, the losses are associated to frequency.

In Table-I, generic comparison of discussed techniques is presented. For the coaxial probe technique (non-resonant method) it can work over the broad range of frequencies and can used for high-loss samples. But it needs repetitive calibrations also air-gaps can cause some errors. Transmission line (waveguide) method is to use measure electric and magnetic properties at high frequency range, it can use for solid & liquid samples but sample preparation is quite difficult than other. Using free-space method a wide frequency range can be use with non-contact testing (as in coaxial probe), a small and flat sample can be used. Problem for the large size samples as low end limited by practical sample size and diffraction from sample edges can cause errors. The most accurate method is resonant cavity with supports liquid and solid samples but limited to low loss and for small size samples only. It is suitable can able to take measurement on single or set of frequency also it doesn't require repetitive calibration.

A low frequency measuring technique is parallel plate capacitor (electrode method) it has moderate accuracy for measuring high-loss materials. It is suitable for thin and flat surface samples. Errors can be introduces due to electrode polarization effect. Another most simple and rapid method which doesn't need special sample handling is planar transmission line method. Test material either can be used as substrate or superstrate; the resonant frequency shift is more prominent for the high loss dielectric samples rather than low loss samples.

Table 1. Comparison of Most Popular Dielectric Measuring Techniques*

Method	*Measure*	*Advantages*	*Drawbacks*
Coaxial Probe	ε_r	• Broadband frequency • Simple and convenient (non-destructive) • Best for semi-solids or liquids • Simple sample preparation • Isotropic and homogeneous material • High accuracy for high-loss materials	• Air gaps causes errors • Repetitive calibrations
Transmi-ssion line (waveg-uide)	ε_r , μ	• High frequency • Support for both solids & liquids • Anisotropic material	• Cannot use below few GHz, due to practical sample length limitation • Sample preparation is difficult (fills fixture cross section)
Free Space	ε_r , μ	• Wide frequency range support • Non-contacting • Easy sample preparation • Moderate accuracy for high-loss & low-loss • Best for large flat and solid materials • Useful for high temperature	• Diffraction problem (from material edges) • Low end limited by practical sample size
Rsonant Cavity	ε_r , μ	• Support for both solids & liquids • Most accurate method • Suitable for low loss materials • No repetitive calibration procedure • High temperature capability • Best for low loss materials	• Measurements at only single or at resonant frequency • Suitable for small size samples
Parallel Plate	ε_r	• Higher accuracy • For thin, flat surface samples • Suitable for high-loss materials • Measurements relatively easier	• Support for low frequency (best results) • Electrode polarization effect
Planar Transmi-ssion	ε_r	• Simple, cost-effective and rapid • No special sample handling • Can used for Solid/Liquid • High temperature measurements	• Low quality factor • Air gap causes error

*References gathered from [4, 8, 10, 12, 15]

4. CONCLUSION

In recent decade, the dielectric property of materials has gain significance in industrial applications. These properties provide useful information to improve the design, processing, quality and control of product. While selecting an appropriate measuring technique it is required to consider various factors like; measuring frequency, testing material & its nature, required accuracy, measurement temperature and losses associated to materials. As these properties are dependent on frequency and temperature; behavior of a material is dynamic. As the frequency increases the dielectric constant of a material is decreases, and in turn the loss factor is increases. For temperature, as it increases the dielectric constant also increases for low permittivity materials but this relation is inverse for the high permittivity materials.

In this paper we have seen that at lower and medium frequency resonant method is more preferable where as at higher frequency transmission line, coaxial, resonant-cavity and free-space methods are commonly used. Parallel plate (electrode), coaxial probe and free-space methods has shown good performance for the high loss materials while resonant cavity gives higher accuracy for the low permittivity materials. However, a good technique should able to provide higher-accuracy, lower cost, easy procedure, rapid measurements for the desire (either high or low loss) testing material.

REFERENCES

[1] S. H. A. Peyman, C. Gabriel, "Dielectric Properties of Tissues at Microwave Frequencies," Physics in Medicine and Biology, vol. 52 pp. 2229-2245, 2007.

[2] P. G. B. Stuart O. Nelson, "Measuring Frequency and Temperature Dependent Permittivities of Food Materials," in IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, 2002, pp. 589-592.

[3] A. P. G. a. R. N.C., "A Review of RF and Microwave Techniques for Dielectric measurement on polar liquids," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 13, pp. 727-743, 2006.

[4] Agilent-Technologies, "Basics Of Measuring The Dielectric Properties Of Material," CA, USA2006.

[5] M. Castro-Giráldez, et al., "Low-frequency dielectric spectrum to determine pork meat quality," Innovative Food Science and Emerging Technologies, vol. 11, pp. 376-386, 2010.

[6] P. J. é. F. Marta Castro - Gir á ldez , Fidel Toldr á , Pedro Fito, Physical Sensors for Quality Control during Processing - Handbook of Meat Processing: A John Wiley & Sons, Inc., 2010.

[7] M. D. J. James Baker-Jarvis, and Donald C. DeGroot, "High-Frequency Dielectric Measurements," IEEE Instrumentation & Measurement Magazine, pp. 24 - 31, 2010, April

[8] G. S. V. R. M.S.Venkatesh, "An Overview of Dielectric Properties Measuring Techniques," The Journal of The Canadian Society for Bioengineering (CSBE), vol. 47, pp. 7.15-7.30, 2005.

[9] M. F. S. Kashif Saeed, Matthew B. Byrne, Ian C. Hunter Ed., Planar Microwave Sensors for Complex Permittivity Characterization of Materials and Their Applications (Applied Measurement Systems. In-Tech, 2012, pp. 319-350.

[10] S. N. Shyam Narayan Jha, K. Basediya, A. Sharma, Rajiv Jaiswal, Pranita Kumar, Ramesh Bhardwaj, Rishi, "Measurement techniques and application of electrical properties for nondestructive quality evaluation of foods—a review," Journal of Food Science and Technology, vol. 48, pp. 387-411, 2011.

[11] F. J. K. B. O. V. Tereshchenko, F. B. J. Leferink, "An overview of the techniques for measuring the dielectric properties of materials," in General Assembly and Scientific Symposium, 2011 XXXth URSI, 2011, pp. 1-4.

[12] F. H. S. Wee, P. J. Suhaizal, A. H. M. Nornikman, H. Ezanuddin, A. A. M., "Free space measurement technique on dielectric properties of agricultural residues at microwave frequencies," in Microwave and Optoelectronics Conference (IMOC), 2009 SBMO/IEEE MTT-S International, 2009, pp. 183-187.

[13] J. M. G. P.A. Bernard, "Measurement of Dielectric Constant using a Microstrip Ring Resonator," IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES,, vol. 39, 1991.

[14] J. V. R. Zajíček, K. Novotný, "Evaluation of a Reflection Method on an Open-Ended Coaxial Line and its Use in Dielectric Measurements," Journal of Advanced Engineering, Acta Polytechnica, vol. Vol. 46 2006.

[15] S. Clerjon and J.-L. Damez, "Microwave sensing for an objective evaluation of meat ageing," Journal of Food Engineering, vol. 94, pp. 379-389, 2009.

AUTHOR PROFILES

1. Muhammad Taha received bachelor's degree in Electrical Technology followed by masters in Telecommunication, in 2007 & 2009 respectively. He is currently working toward PhD in the area of dielectric material characterization using RF & Microwave frequencies at Universiti Teknologi PETRONAS, Malaysia.

2. Muhammad Zaka ur Rehman received the B.S. degree in Electronics from COMSATS Institute of Information Technology, Islamabad, Pakistan in 2007, the MSc Degree in Digital Signal Processing in Communication Systems from Lancaster University, UK, in 2010, and is currently working toward the PhD degree in Electrical Engineering (with an emphasis on RF and Microwave Circuits) at the Universiti Teknologi PETRONAS, Perak, Malaysia. His research interests include RF MEMS for Microwave applications, Substrate Integrated waveguide structures and reconfigurable filters design.

3. Abid Muhammad Khan received BE and ME degree in Electronics engineering from NED University Karachi. He is doing PhD in the area of OFDM channel estimation in the presence of ICI at Universiti Teknologi PERTRONAS, Malaysia. Currently, he is an Assistant Professor at Sir Syed University of Engineering, Karachi.

4. Muhammad Talha Khan received his BS in Electronics engineering from Sir Syed University of Engineering, Karachi. He is a currently doing his M.Sc from Universiti Teknologi PERTRONAS, Malaysia. His research area in design & implementation of BPF & Amplifier using DGS techniques.

5. Syed Muzamil Ali was born in 1987 in Karachi, Pakistan. He received his bachelor degree from COMSATS Institute of Information Technology, Islamabad, Pakistan in 2011. He is a student of M.Sc in Electrical and Electronics Engineering by Reasearch at Universiti Teknologi PERTRONAS, Malaysia currently. His research interests include microstrip antenna and Dielectric Resonator Antenna designing.