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Establishment of measurement traceability of dielectric-constant measurement using contact and non-contact methods

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ABSTRACT
To meet industry demands, measurement traceability for the dielectric constant of solid reference materials has been established at audio and radio frequencies. The dielectric constant is determined using capacitance-based contact and non-contact methods, where the dielectric material is sandwiched between the electrodes of a dielectric test fixture. A precision LCR meter measures the capacitance of solid dielectric materials, and results from contact and non-contact methods align well up to 1 MHz. Measurement uncertainty is evaluated according to the Guide to the Expression of Uncertainty in Measurement, with a detailed discussion of contributing factors.

Section: RESEARCH PAPER

Keywords: Dielectric constant; metrological traceability; parallel-plate-capacitor method; uncertainty in measurement

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1. INTRODUCTION

The demand for high-value and low-value dielectric materials has increased exponentially along with the progress in microelectronics technology. Dielectric materials play a vital role in the performance of electronic equipment widely used in communication, navigation, power generation & distribution systems, instrument control systems and microwave & optical sensors. They are also used in electronic circuits, power transmission lines and capacitors. Hence, dielectric materials are the essential part of any electronics circuit. Capacitors are also used for energy storage due to dielectric polarization (re-orientation of charge particles and electric dipoles under the influence of an external electric field) [1]. Currently, many research groups are working on high temperature dielectric materials for electrical energy storage [2]-[3].

The quality of dielectric materials governs its applications in specific industrial sector. Different types of reference materials are utilized in food industry, pharmaceutical, healthcare, semiconductor and power plant industries. The quality of the reference material plays a crucial role to control the output of product [4]. The structural, compositional, and other properties may be manipulated according to requirements and applications, but prior to this, a detailed investigation of properties such as dielectric constant and losses must be conducted [4]-[14].

Majority of the dielectric materials are strong function of frequency and sensitive to the environmental conditions such as temperature and relative humidity. Thus, it is important to characterize the dielectric materials with good precision, especially for space and military applications.

A number of techniques are used to measure the dielectric-constant over the spectrum [5]-[16]. The resonance and transmission or reflection methods are the two commonly used dielectric-constant measurement methods. Resonance methods are highly accurate but limited to a narrow frequency band while transmission or reflection methods require waveguide which further needs a sample with waveguide cross-section [13]. The low-loss dielectric substrate materials reduce the attenuation and heating in ac circuits and devices. They also reduce the crosstalk between the signals in the printed-circuit-boards. Low-dielectric-constant materials are used for the development of antennas using micro-strip and co-planar waveguide structures.

On the other hand, materials with a high dielectric-constant are also used to miniaturize electrical and electronic systems and to realize high-value capacitors [17]-[20].

Here, we propose dielectric-constant measurement by using contact and non-contact methods using capacitance-based techniques at audio and radio frequencies. The dielectric test fixture used to measure the dielectric-constant is in compliance with ASTM D-150 [8]. The real-part of the dielectric-constant of solid dielectric materials is computed from capacitance that is measured using precision LCR meter (Keysight, 4980A) where dielectric material is placed in a dielectric-test fixture (Keysight, 16451B, Electrode Type B). Poly-Tetra-Fluoro-Ethylene (PTFE) is used as reference dielectric material while fiberglass reinforced epoxy laminates (FR4), quartz and alumina are used as sample dielectric materials. FR4 is a low cost (compared to PTFE) with good mechanical properties, and it is used as a substrate material from audio to microwave frequencies [21] whereas PTFE is the very low loss dielectric material with relatively low dielectric constant.

2. THEORETICAL BACKGROUND

Dielectrics are the insulating materials which transmits electrical effect without actually conducting electricity. They get polarized in the presence of an external field and are classified as polar and non-polar dielectric materials. Basically, they have few free-charge carriers, which are bounded as compared to metals and semiconductors which are responsible for conduction current [18]. The complex dielectric-constant provides information about the electric energy storage and loss factor in the dielectric material, and it is also the function of frequency and temperature mainly [22], [23].

The dielectric-constant, ε_r is a complex quantity; real part (ε_r') represents the electrical energy storage capability of the material in the presence of an external electric field while the imaginary part) represents the loss in the material. The imaginary part is a function of dielectric loss mechanism ε_d'' and free charge conductivity σ as depicted in equation (1):

$$\varepsilon_\mathrm{r} = \varepsilon_\mathrm{r}' - \mathrm{j}\,\varepsilon_\mathrm{r}'' = \varepsilon_\mathrm{r}' - \mathrm{j}\left(\varepsilon_\mathrm{d}'' + \frac{\sigma}{\omega\,\varepsilon_0}\right). \tag{1}$$

The accurate measurement of the reference dielectric material is necessary for the reliable, better performance and miniaturization of electronic circuits/ systems. The selection of dielectric measurement techniques depends on the type and shape of sample and frequency of interest. The dielectric-constant may be calculated as per the user manual [24] for the circular disk electrodes

$$\varepsilon_r' = \frac{t \cdot C_\mathrm{m}}{\pi\,(d/2)^2\,\varepsilon_0}, \tag{2}$$

where t represents thickness of the dielectric sample, C_m represents parallel capacitance measured using precision LCR meter and d represents diameter of the guarded electrode. The uncertainty in dielectric-constant measurement is dependent on the uncertainty contribution from the thickness, parallel capacitance and diameter of the dielectric sample as in equation (2). The dielectric sample is assumed to have a good surface finish, flatness and electrodes of dielectric test fixture are parallel to each other. While, in the proposed work, method based on equation (4) is adopted for the measurement of the real part of dielectric constant of solid dielectric materials for contact method instead of equation (2).

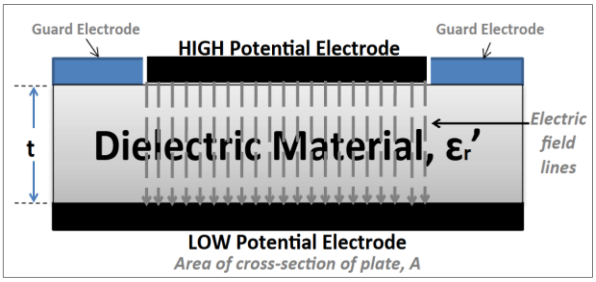

Figure 1. Capacitance technique with contact method.

3. CONTACT METHOD

Generally, a capacitance-based technique is employed to compute the dielectric-constant up-to radio frequency (RF) [25]. The capacitance-based techniques are simple, accurate, reliable and low-cost technique to measure the dielectric-constant of solid, soft and liquid dielectric materials at low to RF [7], [10], [26], [27]. The capacitance-based techniques are affected by the fringing fields and electrode polarization especially at low frequencies [18].

The parallel-plate capacitance as shown in Fig. 1 can be defined as:

$$C_m = \frac{\varepsilon_\mathrm{r}'\,\varepsilon_0\,A}{t}, \tag{3}$$

where ε_0 is the absolute permittivity of free space, A is the area of the cross-section of the plates and d is the separation between the plates as shown in Figure 1. (When there is no air-gap present, $D = t$).

The proposed work for the determination of dielectric-constant is based on the ratio of capacitance in the presence of dielectric material (C_m) and reference capacitance without dielectric material (C_0) as shown in equation (4). Where C_1 and C_2 are the sensitivity coefficients while $u(\varepsilon_\mathrm{r}')$ represents the standard uncertainty in dielectric measurement using the contact method as shown in equation (5), (6) and (8).

$$\varepsilon_\mathrm{r}' = \frac{C_\mathrm{m}}{C_0} \tag{4}$$

$$C_1 = \frac{\partial \varepsilon_\mathrm{r}'}{\partial C_\mathrm{m}} = \frac{1}{C_0} \tag{5}$$

$$C_2 = \frac{\partial \varepsilon_\mathrm{r}'}{\partial C_0} = \frac{-C_\mathrm{m}}{{C_0}^2} \tag{6}$$

$$u(\varepsilon_\mathrm{r}') = \sqrt{\left(\frac{\partial \varepsilon_\mathrm{r}'}{\partial C_\mathrm{m}}\Delta C_\mathrm{m}\right)^2 + \left(\frac{\partial \varepsilon_\mathrm{r}'}{\partial C_0}\Delta C_0\right)^2} \tag{7}$$

$$u(\varepsilon_\mathrm{r}') = \sqrt{\left(\frac{1}{C_0}\Delta C_\mathrm{m}\right)^2 + \left(\frac{-C_\mathrm{m}}{{C_0}^2}\Delta C_0\right)^2}\,. \tag{8}$$

4. NON-CONTACT METHOD

Non-contact method may also be used for solid materials, but it is especially useful for the characterisation of soft and flexible dielectric materials as shown in Figure 2.

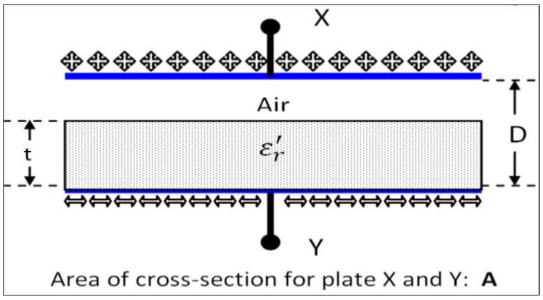

Figure 2. Parallel plate capacitance technique with non-contact method. [19].

The effective capacitance C_e may be seen as the series combination of capacitance due to air dielectric with thickness $(D - t)$ and dielectric material with thickness t as shown in Figure 2. Thus, the effective capacitance C_e for non-contact method may be written as

$$\frac{1}{C_\mathrm{e}} = \frac{1}{C_\mathrm{t}} + \frac{1}{C_{\mathrm{D-t}}} = \frac{t}{\varepsilon_\mathrm{r}' \, \varepsilon_0 \, A} + \frac{D - t}{\varepsilon_0 \, A} \, . \tag{9}$$

Then, the dielectric constant, $\varepsilon_\mathrm{r}^{'}$ may be computed in terms of C_0, C_e, D and t with the following expression:

$$\varepsilon_\mathrm{r}' = \frac{1}{1 - \frac{D}{t}\left[1 - \left(\frac{C_0}{C_\mathrm{e}}\right)\right]} \, , \tag{10}$$

where C_0 is the measured capacitance between the plates when there is no dielectric material placed in between the plates (where D is the separation between the plates). It can be expressed as

$$C_0 = \frac{\varepsilon_0 \, A}{D} \, , \tag{11}$$

where C_e is the measured capacitance between the plates when there is a dielectric material with dielectric constant $\varepsilon_\mathrm{r}^{'}$ of thickness t placed in between the plates (where D is the separation between the plates) as shown in Figure 2. It can be expressed as:

$$C_\mathrm{e} = \frac{\varepsilon_\mathrm{r}' \, \varepsilon_0 \, A}{D} \, . \tag{12}$$

The standard uncertainty $u(\varepsilon_\mathrm{r}^{'})$ for non-contact method may be written as:

$$u(\varepsilon_\mathrm{r}^{'}) = \sqrt{\left(\frac{\partial \varepsilon_\mathrm{r}'}{\partial \mathrm{C_m}} \Delta \mathrm{C_m}\right)^2 + \left(\frac{\partial \varepsilon_\mathrm{r}'}{\partial \mathrm{C_0}} \Delta \mathrm{C_0}\right)^2 \left(\frac{\partial \varepsilon_\mathrm{r}'}{\partial \mathrm{D}} \Delta \mathrm{D}\right)^2 + \left(\frac{\partial \varepsilon_\mathrm{r}'}{\partial \mathrm{t}} \Delta \mathrm{t}\right)^2} \, . \tag{13}$$

The dielectric-constant measurement is traceable to the national/reference standard of impedance (capacitance) and length which are being maintained at CSIR-National Physical Laboratory [28], [29].

5. MEASUREMENT SETUP

The measurement setup for the determination of the dielectric-constant includes the precision LCR meter, which is traceable to the National standard of capacitance and a dielectric test fixture. Dielectric test fixture (Keysight, 16451B, Electrode Type B) with guard electrode is used to minimize the uncertainty due to fringing field effect in parallel plate electrodes. Guarded electrode is used as high-potential electrode as shown in Figure 3 [26]. Type B electrode allows samples with thickness ≤ 10 mm and diameter from 10 mm to 56 mm whereas Type A electrode can accommodate the sample with diameter from 40 mm to 56 mm only.

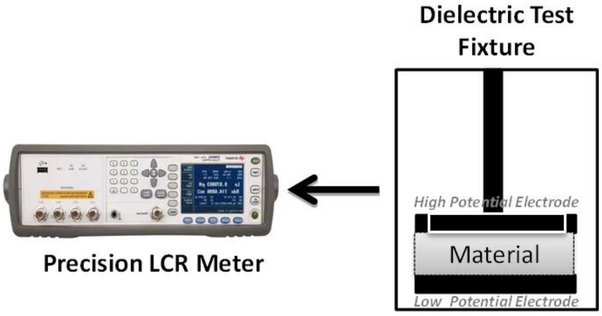

Figure 3. Measurement setup for dielectric-constant measurement facility.

The measurement-automation program for the dielectric-constant measurement is developed in LabVIEW programming-environment and IEEE 488.2 interface is utilized as a communication interface between PC and precision LCR meter. The measurement-automation program configures and controls the functionality of precision LCR meter, computes dielectric-constant, guides the user throughout the measurement procedure.

6. COMPUTATION OF DIELECTRIC CONSTANT

The fixture compensation is performed using an OPEN-SHORT method which includes cable compensation as well. An LCR meter is used to measure the capacitance with and without the dielectric material and thereafter dielectric-constant and associated uncertainty are computed. The uncertainty-in-measurement is computed as per the “Guide to the expression of uncertainty in measurement” [30].

Initially, the Teflon sample is used as a reference material for dielectric-constant measurement for contact and non-contact techniques. The computed dielectric-constant for Teflon sample is in agreement with previous work [18] as shown in Table 1.

Thereafter, dielectric-constants of FR4, quartz and alumina (Al_2O_3) samples are measured and compared using both above mentioned methods. The detailed uncertainty budget for Al_2O_3 dielectric sample material at 1 MHz is shown in Table 2. The measured dielectric constant of Al_2O_3 is 9.311 with standard uncertainty (± 0.513).

7. SUMMARY AND DISCUSSION

The factors contributing to the uncertainty-in measurement of dielectric-constant are as follows:

Table 1. Dielectric-constant of Teflon sample as reference using contact and non-contact techniques.

Freq. in kHz	Contact			Non-contact		
	$\varepsilon_r' \pm u(\varepsilon_\mathrm{r}')$		$\frac{\Delta\varepsilon_r'}{\varepsilon_r'}$ in %	$\varepsilon_r' \pm u(\varepsilon_\mathrm{r}')$		$\frac{\Delta\varepsilon_r'}{\varepsilon_r'}$ in %
1	1.969	0.008	6.24	1.971	0.006	6.14
10	2.000	0.008	4.76	1.967	0.006	6.33
100	1.995	0.008	5.00	1.961	0.006	6.62
1000	1.998	0.009	4.86	1.964	0.006	6.48

- Surface roughness: The surface roughness of the sample contributes to the uncertainty-in-measurement. It creates an airgap between sample and electrode which forms the parasitic capacitance. The repeatability of dielectric constant measurement is also affected due to surface roughness of the sample material.
- Parallelism: Parallelism between the electrodes and sample material is the essential requirement for dielectric-constant measurement. Any deviation in the parallelism of electrodes will degrade the repeatability of dielectric-constant measurement.
- Uncertainty of the LCR meter
- Temperature-coefficient of sample dielectric material
- Stability of measurement setup (includes test-fixture and LCR meter)

The temperature-coefficient of dielectric material and stability of the measurement setup is found to be in-significant in the frequency range of interest as compared to the surface roughness of sample materials and parallelism between the electrodes of test fixture. The linearity of the test fixture is analysed by measuring the change in capacitance between the guarded and un-guarded electrodes as a function of displacement. The linearity is one of the critical parameters which may contribute to the uncertainty-in-measurement of dielectric-constant. The linearity of the test fixture is analysed, and the correlation coefficient is found to be close to unity in the desired frequency range.

Table 3 shows a comparison of dielectric measurement results obtained using contact and non-contact methods, while Table 4 summarizes the results from both methods.

8. CONCLUSION

The metrological traceability of dielectric-constant of solid dielectric materials is established using the contact and non-contact methods up-to 1 MHz. The uncertainty-in dielectric-constant measurement is computed as per the GUM document. The factors affecting the uncertainty in measurement are analysed and discussed. The computed dielectric constant and their uncertainties are compared for contact and non-contact method and are in good agreement with each other. The uncertainty achieved using non-contact method is higher than the contact method as it is dependent on uncertainties due thickness of sample and air gap between the guarded electrode and sample. The dielectric test fixture maybe further modified to improve the uncertainty in dielectric-constant measurement.

Table 2. Uncertainty budget for alumina sample material for non-contact method.

Al$_2$O$_3$ Material @ 1 MHz							
Quantity	**Estimate**	**Relative Standard Uncertainty**	**Probability Distribution**	**Sensitivity Coefficient**	**Unit**	**Uncertainty Contribution**	**Unit**
C_m, F	$2.28\cdot10^{-13}$	$7.45\cdot10^{-17}$	Normal	$5.27\cdot10^{11}$	1/F	$1.54\cdot10^{-9}$	Unitless
C_0, F	$7.41\cdot10^{-14}$	$1.46\cdot10^{-16}$	Normal	$-1.62\cdot10^{12}$	1/F	$5.61\cdot10^{-8}$	Unitless
t, m	0.002	0.00001	Normal	$-4.09\cdot10^{4}$	1/m	$9.58\cdot10^{-2}$	Unitless
D, m	0.003	0.00001	Normal	$3.10\cdot10^{4}$	1/m	$1.68\cdot10^{-1}$	Unitless
ε_r'	9.311		$k = 1$			± 0.513	

Table 3. Comparison of dielectric-constant computed using contact and non-contact methods from 1 kHz to 1 MHz and their standard uncertainty

Dielectric Material	Frequency in kHz	Contact			Non-contact		
		ε_r'	$\pm\,u(\varepsilon_\mathrm{r}')$	$\frac{\Delta\varepsilon_\mathrm{r}'}{\varepsilon_\mathrm{r}'}$ in %	ε_r'	$\pm\,u(\varepsilon_\mathrm{r}')$	$\frac{\Delta\varepsilon_\mathrm{r}'}{\varepsilon_\mathrm{r}'}$ in %
FR4	1	4.751	0.006	--	4.837	0.160	--
	10	4.756	0.006	--	4.872	0.163	--
	100	4.742	0.006	--	4.887	0.164	--
	1000	4.753	0.007	--	4.893	0.164	--
Quartz	1	3.585	0.007	--	3.651	0.064	--
	10	3.593	0.007	5.94	3.646	0.064	4.55
	100	3.585	0.007	--	3.681	0.065	--
	1000	3.592	0.006	5.97	3.686	0.065	3.51
Alumina	1	9.138	0.019	--	9.284	0.510	--
	10	9.117	0.018	3.83	9.204	0.501	2.91
	100	9.144	0.021	--	9.253	0.507	--
	1000	9.119	0.020	3.40	9.311	0.513	1.37

Table 4. Comparison of contact and non-contact methods for measurement of dielectric constant.

Parameters	Contact Method	Non-Contact Method	Comments
Sample material requirements	Solid dielectrics with homogeneous, flat, smooth surface finish	Soft, flexible and brittle solid dielectrics with homogenous, flat and good surface finish	Uncertainty in non-contact method is the function of four parameters (Capacitance with or without dielectric, thickness of dielectric sample and total separation between plates)
Complexity	Low	Medium	
Accuracy	High	Medium	
Uncertainty	Low	Medium	

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REFERENCES

[1] H. S. Nalwa, Handbook of low and high Dielectric Constant Materials and their Applications., Academic Press, 1999, ISBN 978-012-523905-2.

[2] X. Hao, A review on the dielectric materials for high energy-storage application, Journal of Advanced Dielectrics 03 (2013) 1. DOI: 10.1142/S2010135X13300016

[3] Q. Li, F. Z. Yao, Y. Liu, G. Zhang, H. Wang, Q. Wang, High-Temperature Dielectric Materials for Electrical Energy Storage, Annual Review of Materials Research 48 (2018) pp. 219-243. DOI: 10.1146/annurev-matsci-070317-124435

[4] H. Czichos, T. Saito, L. Smith, Handbook of Metrology and Testing, 2011, ISBN 978-3-642-16640-2, pp. 485-540.

[5] A. P. Gregory, G. J. Hill, M. A. Barnett, Low loss dielectric measurements in the frequency range 1-70 MHz by using a vector network analyser, Meas. Sci. Technol. 32 (2021) 8.
DOI: https://doi.org/10.1088/1361-6501/abfd68

[6] A. C. Lynch, Precise Measurements on Dielectric and Magnetic Materials, IEEE Trans. Instrum. Meas., 23 (1974) 4, pp. 425–431. DOI: 10.1109/TIM.1974.4314327

[7] T. T. Grove, M. F. Masters, R. E. Miers, Determining dielectric constants using a parallel plate capacitor, Am. J. Phys., 73 (2005) 1, pp. 52–56.
DOI: 10.1119/1.1794757

[8] ASTM International, Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation, 2022. Online [Accessed 10 June 2025]
https://store.astm.org/d0150-18.html

[9] K. Fenske, D. Misra, Dielectric Materials at Microwave Frequencies, Applied Microwave and Wireless, 2000, pp. 92–100. Online [Accessed 10 June 2025]
https://www.n5dux.com/ham/files/pdf/Dielectric%20Materials%20at%20Microwave%20Frequencies.pdf

[10] Agilent Technologies, Basics of Measuring the Dielectric Properties of Materials, Application Note, 2006. Online [Not available on 10 June 2025]
https://www.keysight.com/us/en/assets/7018-01284/application-notes/5989-2589.pdf

[11] Michael J. Hill, L. E. Wojewoda, A Study of Permittivity Measurement Reproducibility Utilizing the Agilent 4291 B, IEEE Transactions on Advanced Packaging 29 (2006) 4, pp. 714-718. DOI: 10.1109/TCAPT.2006.888210

[12] C. S. Geyik, M. J. Hill, Z. Zhang, K. Aygün, J. T. Aberle, Impact of Measurement Uncertainty on Correlation Quality for High-Speed Interconnects, IEEE Transactions On Components, Packaging and Manufacturing Technology 11 (2021) 9, pp. 1380-1390.
DOI: 10.1109/TCPMT.2021.3101456

[13] M. Celuch, M. J. Hill, T. Karpisz, M. Olszewska-Placha, S. Phommakesone, U. Ray, Bridging the materials' permittivity traceability gap for 5G applications, 2021 IEEE Int. Symp. Antenna & Propagation and USNS –URSI Radio science meeting, Singapore, 4-10 December 2021, pp. 859-60.
DOI: 10.1109/APS/URSI47566.2021.9704374

[14] I. Lenicek, V. Milardic, Reference Standard of Low-Frequency Electric Field Strength with Electrical Traceability, IEEE Transactions on Instrumentation and Measurement, 72 (2023) pp. 1007608.
DOI: 10.1109/TIM.2023.3296818

[15] A. Santana, A. Valenzuela, Non-destructive measurement of the dielectric constant of solid samples, Rev. Mex. F´ISICA 55 (2009) 6, pp. 477–485. Online [Accessed 10 June 2025]
https://www.redalyc.org/pdf/570/57013233012.pdf

[16] J. Yoon, J. Kwon, H. Lee, The Microwave Measurement of the Dielectric Properties by the Parallel Plate Resonator and Ceramic Cavity Method, Proc. 5th Int. Conf. Prop. Appl. Dielectr. Mater., Seoul, Korea (South), 25-30 May 1997, pp. 964–968.

[17] J. B. Jarvis, M. D. Janezic, B. Riddle, C. L. Holloway, N. G. Paulter, J. E. Blendell, Dielectric and Conductor-Loss Characterization and Measurements on Electronic Packaging Materials, NIST Technical Note 1520, 2001.
DOI: https://doi.org/10.6028/NIST.TN.1520

[18] R. G. Geyer, Dielectric Characterization and reference Materials, NIST Technical Note 1338, 1990. Online [Accessed 10 June 2025]
https://www.nist.gov/publications/dielectric-characterization-and-reference-materials

[19] C. Gabriel, A. Peyman, Dielectric measurement : error analysis and assessment of uncertainty, Phys. Med. Biol., 51 (2006) pp. 6033–6046,.
DOI: 10.1088/0031-9155/51/23/006

[20] A. P. Gregory, R. N. Clarke, Dielectric metrology with coaxial sensors, Meas. Sci. Technol., 18 (2007) 5, pp. 1372–1386.
DOI: 10.1088/0957-0233/18/5/026

[21] E. L. Holzman, Wideband measurement of the dielectric constant of an FR4 substrate using a parallel-coupled microstrip resonator, IEEE Trans. Microw. Theory Tech., 54 (2006) 7, pp. 3127–3130.
DOI: 10.1109/TMTT.2006.877061

[22] J. G. Webster, H. Eren, Measurement, instrumentation, and sensors handbook: Spatial, mechanical, thermal, and radiation measurement, second edition, CRC Press, 2017, ISBN: 9781138072176.

[23] J. Walker, Fundamentals of Physics, 11th ed. Wiley, 2020, ISBN: 978-1-119-30685-6.

[24] Keysight 16451B Dielectric Test Fixture, Keysight Technologies, 2008. Online [Accessed 10 June 2025]
https://www.keysight.com/in/en/product/16451B/dielectric-test-fixture.html

[25] W. Jee, K. Raymond, C. Kumar, G. Chin, A. Basri, Complex permittivity measurement using capacitance method from 300 kHz to 50 MHz, Measurement, 46 (2013) 10, pp. 3796–3801.
DOI: 10.1016/j.measurement.2013.06.039

[26] C. Cooke, J. E. Ford, Accurate measurement of the dielectric constant of solids, J. Phys. E., 14 (1981).
DOI: 10.1088/0022-3735/14/11/015

[27] V. Hartwig, G. Giovannetti, N. Vanello, M. Costantino, L. Landini, A. Benassi, An electrodeless system for measurement of liquid sample dielectric properties in Radio Frequency band, An electrodeless system for measurement of liquid sample dielectric properties in Radio Frequency band, Proc. of the 28th IEEE EMBS Annual Int. Conf., New York City, USA, 30 August – 3 September 2006, pp. 4127–4130.

[28] Satish, S. Kumar, Babita, T. John, A. K. Saxena, Realization of coaxial reference air-lines as high frequency capacitance standard at CSIR-NPL, Measurement, 92 (2016), pp. 166–171.
DOI: 10.1016/j.measurement.2016.06.017

[29] S. Singh, S. Kumar, Babita, T. John, Realization of Four-Terminal-Pair Capacitors as Reference Standards of Impedance at High Frequency Using Impedance-Matrix Method, IEEE Trans. Instrum. Meas., vol. 66, no. 08, 2017, pp. 2129–2135.
DOI: 10.1109/TIM.2017.2673098

[30] Joint Committee For Guides In Metrology, Evaluation of measurement data — Guide to the expression of uncertainty in measurement, JCGM/Working Group 1, Ed.; 2008. Online [Accessed 10 June 2025]
https://www.bipm.org/en/committees/jc/jcgm/publications