Measuring Complex Permittivity of Dielectric Materials at VHF/UHF Frequencies using a Radio Frequency Capacitive System

1. Scope

1.1 This test method covers a procedure for determining complex permittivity from bulk materials and composites.

1.2 This measurement method is valid over a frequency range of approximately 80 – 800 MHz. These limits are not exact and depend on the specific design of the Radio Frequency (RF) capacitive system.

1.3 The values stated in SI units are to be regarded as the standard. The values given in parentheses are in English units. The equations shown here assume an $e^{+j\omega t}$ harmonic time convention.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ISBN 1480092851 Focused Beam Methods: Measuring Microwave Materials in Free Space, J.W. Schultz, 2012

3. Terminology

3.1 For other definitions used in this test method, refer to ISBN 1480092851 Focused Beam Methods.

3.2 *Definitions:*

3.2.1 *Relative complex permittivity (relative complex dielectric constant)*, ε_r^*—the proportionality factor that relates the electric field to the electric flux density, and which depends on intrinsic material properties such as molecular polarizability, charge mobility, etc.:

$$\boldsymbol{\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'' = \frac{\vec{D}}{\varepsilon_0 \vec{E}}} \qquad (1)$$

where

ε_0= the permittivity of free space,

$\vec{D}$ = the electric flux density vector, and

$\vec{E}$ = the electric field vector.

3.2.1.1 *Discussion*—In common usage the word "relative" is frequently dropped. The real part of complex relative permittivity (ε_r') is often referred to as simply relative permittivity, permittivity or dielectric constant. The imaginary part of complex relative permittivity (ε_r'') is often referred to as the loss factor. In anisotropic media, permittivity is polarization dependent and described by a three-dimensional tensor.

3.2.1.2 For the purposes of this test method only one tensor component of the media is measured at a time, and therefore permittivity is a single complex number at each frequency. The specimen may be rotated in the fixture for subsequent measurments to obtain the three principal tensor components

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 A list of symbols specific to this test method is given in Annex A1.

3.3.2 *Calibration*— a procedure for correcting systematic errors in the measured reflection response. Measurement of a known standard is used to normalize the measured specimen reflection. The preferred measurement standard is a 3"x2"x2" low-dielectric foam block, which simulates air or no specimen in the fixture. The standard foam block is placed inside the specimen chamber to maintain the spacing to the shorting plate so that it matches the specimen dimension.

3.3.2.1 *Discussion*— For the purposes of this standard there is one level of calibration: i) a response calibration that is applied before every measurement sequence. The response calibration is mandatory and should be conducted as often as is practical.

3.3.3 *Network Analyzer*—a system that measures one-port reflection characteristic of a single-port system in its linear range and at a common input and output frequency.

3.3.3.1 *Discussion*—For the purposes of this standard, this description includes only those systems that have a synthesized signal generator and that measure the complex scattering parameters (both magnitude and phase) of a one-port network (S_{11}).

3.3.4 *Scattering parameter (S-parameter)*, S_{ij}—a complex number consisting of either the reflection or transmission coefficient of a component at a specified set of input and output reference planes with an incident signal on only a single port.

3.3.4.1 *Discussion*—As most commonly used, these coefficients represent the quotient of the complex electric field strength (or voltage) of a reflected or transmitted wave divided by that of an incident wave. The subscripts *i* and *j* of a typical coefficient S_{ij} refer to the output and input ports, respectively. For example, the port 1 reflection coefficient S_{11} is the ratio of the port 1 reflected wave voltage divided by the port 1 incident wave voltage. For this test method, only S_{11} is measured.

4. Executive Summary and Significance

4.1 The fixture consists of a vertically-oriented square coaxial transmission line where the center conductuctor is truncated to allow placement of the specimen in contact with the center conductor. A rectangular or cube shaped specimen may be used as long as it is no wider than the center conductor. A shorting plate is placed on top of the specimen and secured to the outer walls of the square coaxial line to form a shorted transmission line with the specimen inside. Screws around the perimeter of the outer conducture are used to electrically connect the shorting plate to the outer conductor so that no RF energy leaks out of the fixture. A network analyzer is connected to the other end of the square coaxial line via a transition to excite the RF capacitor. A CEM-based inversion algorithm converts the measured amplitude and phase into a corresponding real and imaginary permittivity at each measurement frequency.

4.2 The electric field at the specimen location is vertically oriented between the truncated center conductor and the metal short on top of the specimen. For anisotropic materials, the measured permittivity is in this vertical direction.

4.3 Bulk materials are used to absorb, reflect, or guide electromagnetic energy in a variety of applications. This test method is useful for evaluating the intrinsic properties of dielectrics over a wide frequency range. The horizontal size of the center conductor in the fixture enables inhomogeneous composites (e.g. foams, honeycombs and multilayer constructs) to be characterized as well as simple dielectrics.

5. Restrictions

5.1 This test method uses an inversion technique based on a computational electromagnetic (CEM) model of the specimen under test in the fixture. This inversion compares the measured parameters to a pre-computed look-up table. Therefore the specimen size and shape must correspond to an existing look-up table.

5.2 The specimen size must match the expected size of the used inversion model. Differences between the actual and expected dimensions will lead to systematic errors in the calculated permittivity. Additionally the specimen sides should be flat and parallel to ensure good contact with both the center conductor and the top shorting plate. Unanticipated air gaps between the specimen and these surfaces will lead to measurement errors.

5.3 The specimen must be positioned so that it is centered on the center conductor within the fixture. This is so it corresponds with the CEM-based model which assumes the specimen is centered.

5.4 The shorting plate is clamped to the outer-conductor of the fixture. To ensure good electrical contact the connection must be free of dirt and oxidation. The shorting plate and the fixture must be periodically cleaned to minimize the oxidation layer. Similarly the inside of the fixture must be free of debris.

5.5 The shorted plate is weighted to ensure good electrical contact with the test specimen and to minimize air-gaps. In some cases a soft material such as foam, may experience compression-dependent properties. In these cases, the test method will have increased measurement errors related to this specimen compression within the fixture.

6. Apparatus

6.1 *Experimental Test Fixture*— The fixture consists of a vertically oriented square coaxial transmission line with a truncated center conductor and provision for a top shorting plate as shown in FIG. 1 and FIG 2. The top plate of the fixture must be detachable to enable placement of the specimen within the fixture. When placed, the shorting plate must be secured so that it makes electrical contact with the outer counductor of the fixture. Below the specimen location, the square coaxial line is transitioned to an RF connector connected to a network anlayzer.

6.1.1 *Top shorting plate*— The top shorting plate must be weighted to make good contact with the top of the specimen under test, but not so much that it crushes or deforms the specimen. A weight of approximately 1 to 1.5 kg is preferred.

6.1.2 *Center Conductor*— The center conductor forms the bottom electrode for the RF capacitance measurement. It is centered within the square coaxial geometry. It must be flat and clean to make good electrical contact with bottom side of the specimen under test.

6.2 *Network Analyzer*—The network analyzer must have at least 1-port that can measure vector scatter (S_{11}). The preferred configuration uses a miniaturized 1-port network analyzer connected directly to the fixture, however an RF cable may be used to connect the fixture to a bench-top network analyzer.

6.3 *Response Calibration Kit*—To define the measurement reference and minimize fixture uncertainties, calibration of the test fixture is required. A response calibration procedure must be followed that uses a low-dielectric foam with the same height as the specimens. The foam's relative dielectric constant must be no greater than 1.05.

7. Test Specimen

7.1 The test specimen must be of a size and shape that matches the inversion database to be used to determine complex permittivity. Otherwise, the inversion error will be approximately proportional to the deviation of the specimen sizd to the assumed size in the algorithm. The specimen must be uniform with flat outer surfaces and parallel sides. Damage to ther specimen's surface from cutting or machining will lead to incomplete contact with the center conductor and/or shorting plate, increasing measurement errors.

8. Preparation of Apparatus

8.1 *Inspect Network Analyzer Test Port*— Ensure that the test port and the RF capacitor connector is in good working condition. Refer to the network analyzer manufacturer's documentation to provide connector specifications.

8.2 *Tightening Cables and Connectors*— Improperly tightened connectors introduce phase and magnitude errors into *S*-parameter data. For this reason, tighten the reflectometer's N-type male connector to the RF capacitor's N-port female connector with sufficient torque. If an RF cable is used with this fixture, the length must be minimized to reduce phase errors from thermal expansion of the cable.

8.3 *Network Analyzer Setup*:

8.3.1 Refer to manufacturer documentation for minimum warm-up period for the network analyzer.

8.3.2 Use the network analyzer in stepped frequency mode.

8.3.3 Set the reflectometer variable intermediate frequency (IF) bandwidth to 100 Hz or less for high fidelity measurements.

9. Procedure

9.1 The test procedure includes response or fixture calibration and then a series of specimen measurements.

9.2 Before beginning either a calibration or measurement, the system must be powered on and warmed up so that the network analyzer has reached thermal equilibrium. Refer to the network analyzer manufacturer's documentation for recommended warm-up times.

9.3 *Calibration*:

9.3.1 A clearsite calibration measurement is required before every measurement series. Use the following procedure to obtain the response calibration measurement.

9.3.2 Unlock and remove the top shorting plate to remove any previous specimen from the fixture. Use care to ensure the inside surface of the top plate is not scratched when it is placed to the side.

9.3.3 Place the low-dielectric foam calibration standard on the center conductor so that it is centered inside the fixture.

9.3.4 Replace the top shorting plate so that it rests on top of the calibration specimen, and tightening the screws that secure the top plate to the outer conductor. Ensure that the top plate is not inadvertently tilted during the screw-tightening procedure, and make sure the top plate is sufficiently tightened to have good electrical contact with the outer conductor.

9.3.5 Measure the S_{11} of the RF capacitor over the desired frequency range.

9.3.6 *Response Calibration Frequency*—For best accuracy, repeat the calibration procedure often to minimize phase drift. A preferred tempo is to measure before each new specimen. (A specimen measurement often includes up to three individual measurements – one for each orientation). For any given measurement sequence, the calibration sequence must be conducted at least twice (e.g. calibrate before and after the measurements) to check for temperature or system drift.

9.4 *Measurement Validation*—For every measurement sequence, a validation specimen must also be measured to check for proper system operation. This specimen must be a known material that is measured at least once every day that the system is in use. This provides validation for the measurements of that day and also tracks the accuracy of the measurement system over time.

9.5 *Specimen Measurement*:

9.5.1 When inserted into the fixture, the specimen under test must be centered on the truncated center conductor inside the fixture as shown in FIG. 2.

9.5.2 The procedure follows the same steps as in calibration:

9.5.2.1 Unlock the top plate by loosening the screws and replace the calibration standard with the specimen under test.

9.5.2.2 Replace the top shorting plate and tightening the screws to secure it to the outer conductor. Ensure the top plate maintains good electrical contact with the specimen and stays level while tightening the screws.

9.5.2.3 Measure the S_{11} of the RF capacitor over the desired frequency range

9.5.3 Calculate the permittivity of the specimen(s) from the calibrated S_{11} data, as described in the following Calculation section.

10. Calculation

10.1 As discussed above, the calibrated data is computed by a simple ratio of the specimen measurement data to the response measurement,

$$S_{11}^{calibrated} = \frac{S_{11}^{specimen}}{S_{11}^{response}}$$

10.2 Inversion of the complex permittivity is then calculated from the calibrated S_{11} data. There is no analytic relationship between S_{11} and permittivity, so a series of computational electromagnetic (CEM) model calculations must be conducted to establish this relationship. Specifically the exact geometry of the RF capacitive fixture is modeled with a full-wave finite difference time domain (FDTD) solver for a range of permittivities and conductivities of the unknown specimen. In this way a data table is constructed for a given specimen size.

10.3 Inversion of the complex permittivity is done by a table-lookup algorithm where the measured S_{11} is compared to the pre-computed reflection coefficients from the computational model. The data table is necessarily sparse, so interpolation between data points within the table must be used to increase the precision of the inversion algorithm. To avoid solution branching problems, the algorithm must start at the lowest measured frequency and use bounding to limit the next-higher frequency comparison.

11. Report

11.1 Report the following information:

11.1.1 Operator name, time and date of measurement,

11.1.2 RF Capacitor system infomation,

11.1.3 Network analyzer settings such as start and stop frequencies, number of points, averaging factor / IF bandwidth,

11.1.4 Calculated values of the permittivity of the verification specimen at each measurement frequency,

11.1.5 Test specimen identification and origin,

11.1.6 Specimen dimensions and uncertainties used in data reduction, including general conditions (flatness, homogeneity, etc.), and

11.1.7 Calculated values of permittivity for the test specimen at each measurement frequency.

12. Precision and Bias

12.1 *Precision*—

12.2 The sources of precision error in permittivity measurement include:

12.2.1.1 Errors in measuring the magnitude and phase of the scattering parameters (i.e. network analyzer noise and drift),

12.2.1.2 Interpolation coarseness

12.3 Bias—

12.3.1 The sources of bias error in complex permittivity measurement include:

12.3.1.1 Errors in the specimen dimensions and flatness,

12.3.1.2 Air gap errors (i.e. specimen surface roughness/damage),

12.3.1.3 Specimen alignment errors, and
12.3.1.4 Computational model error (i.e. accuracy of fixture model)

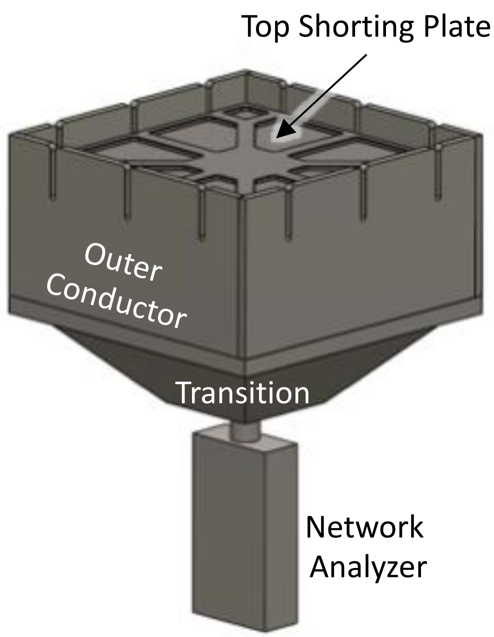

FIG. 1 Diagram of Experimental Fixture

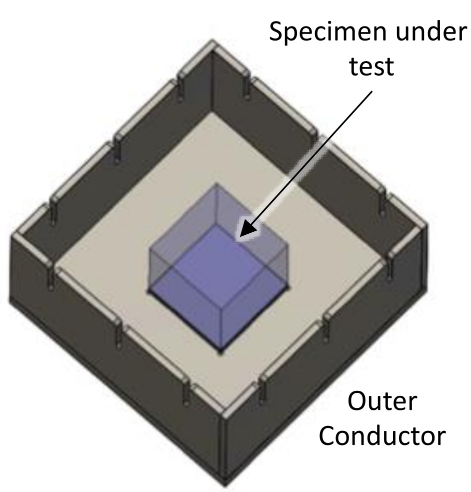

FIG. 2 Diagram of Experimental Fixture with Top Shorting Plate Removed

13. ANNEXES

A1. LIST OF IMPORTANT SYMBOLS

$j = \sqrt{-1}$	The complex constant
f	Measurement frequency (Hz)
$\varepsilon_r^* = \varepsilon_r^{'} - j\varepsilon_r^{''}$	Relative complex permittivity of specimen
S_{ij}	Scattering coefficient from Port j into Port i