Standard Test Method: **CTG-TM-0300-2018** A CTG Standard

Measuring Complex Sheet Impedance of Materials at VHF/UHF Frequencies using a Slotted Rectangular Coaxial Transmission Line

1. Scope

1.1 This test method covers a procedure for determining complex sheet impedance from thin materials

1.2 This measurement method is valid over a frequency range of approximately 60 - 600 MHz. These limits are not exact and depend on specific design of the rectangular coaxial transmission line fixture.

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 *Complex sheet impedance, Z^**—the two-dimensional analog to resistivity, used to characterize thin conductive or semi-conductive sheet materials expressed in ohms per square. In the low frequency limit, sheet resistance can be expressed as the ratio of resistivity to sheet thickness:

$$\boldsymbol{Z}^* = \boldsymbol{Z}' - \mathbf{j}\boldsymbol{Z}'' = \frac{\rho}{t} \qquad (1)$$

where
t = the thickness of the electrically thin material,
ρ = the resistivity,
$\boldsymbol{Z}'$ = the real sheet impedance or resistance, and
$\boldsymbol{Z}''$ = the imaginary sheet impedance or reactance.

3.2.1.1 *Discussion*—While resitivity and resistance are used to describe bulk, (3-dimensional) materials, sheet impedance assumes that the material behaves 2-dimensionally and can be described analogously to a shunt resistor in an electrical circuit. Strictly speaking, sheet impedance units are in ohms. However the convention of ohms per square is used to distinguish it from simple resistance. The addition of "per square" in the units description arises out of the fact that a square sheet of material with a given ohms/square sheet impedance will also have a conventional impedance of the same value, regardless of the size of the square.

3.2.1.2 As a two-dimensional construct, it is possible for a material to have an anisotropic sheet impedance with two principal values. For the purposes of this test method, only one tensor component of the media is measured at a time, and therefore sheet impedance is a single complex number at each frequency.

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 S-parameters from a transmission line fixture. A series of measurements are made of known standards and the systematic errors are then mathematically removed from the indicated measurements. The calibration also establishes the mathematical reference plane for the measurement test ports.

3.3.2.1 *Discussion*—For the purposes of this standard there are two levels of calibration: i) a full waveguide calibration that is applied once every few months or whenever the system has changed sufficiently, and ii) a response calibration that is applied before every measurement sequence. The full calibration is not mandatory, but improves overall system accuracy. The response calibration is mandatory and should be conducted as often as is practical.

3.3.3 *Network analyzer*—a system that measures the two-port transmission and one-port reflection characteristics of a multiport 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 two-port network. More specifically, this procedure requires measurement of one of the transmission S-parameters (S_{21} or S_{12})

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 forward transmission coefficient S_{21} is the ratio of the voltage transmitted to port 2 divided by the incident wave voltage from port 1. Similarly, 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.

4. Executive Summary and Significance

4.1 A thin sheet specimen is inserted into the test fixture through a slot. The test fixture consists of a rectangular coaxial transmission line connected to a network analyzer and the slot goes through both the outer and inner conductors of the transmission line. The insertion of the test specimen changes the transmission amplitude and phase measured by the network analyzer. An inversion algorithm converts the measured amplitude and phase into a corresponding real and imaginary sheet impedance at each frequency measured.

4.2 Resistive 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 sheet materials, whether in small experimental batches or in high-volume production. Specifically the slotted configuration of this device enables non-destructive evaluation of materials in a manufacturing setting as well as individual witness coupons.

5. Restrictions

5.1 The rectangular coaxial method is optimized to have improved sensitivity to materials with very high sheet impedances (> 10,000 ohms/square). As a result, it is less effective than other methods for materials with low sheet impedances (< 200 ohms/square). Furthermore at impedances below 30 ohms/square the method does not work at all.

5.2 The specimen must be centered within the slot to obtain good measurement accuracy. When the specimen is off-center, it can encourage anamolous radiation out of the slot at frequencies corresponding to where the slot length is an integral multiple of a half-wavelength. This restriction is more significant for lower impedances where the problem is exacerbated. In some cases a low-dielectric alignment aid, such as foam board or corrugated cardboard must be used to properly center the specimen in the slot. In a manufacturing setting, external rollers and tensioning must be used to accurately center the specimen under test.

5.3 This test method uses an inversion technique based on a computational model of the specimen under test in the fixture. Inversion compares the measured parameters to a pre-computed database. Therefore the specimen size must correspond to an existing database for that same sized specimen. In some cases, particularly for lower-impedance materials, it is not sufficient just to match the width of the specimen, and the length of the specimen must also match. For example, an inversion database designed for 12”x12” specimens will only be accurate at the lower impedances if the specimens are a square 12”x12” shape. However, at impedances above ~5,000 ohms/square, the specimen no londer needs to be square and a 12”x longer specimen is acceptable. Similar rules apply to other sized specimens.

6. Apparatus

6.1 *Experimental Test Fixture*—The test fixture consists of a 50 ohm rectangular coaxial line with a slot cut through both the inner and outer conductors so that the material specimen can be inserted through the fixture, as shown in Fig. 1. The coaxial line must have transitions at both ends so that it can be connected to a network analyzer.

6.1.1 *Anti-Static Charge Device*—As specimens are dragged through the slot, there is a tendency for a DC charge to build up between the center conductor and outer conductor. This DC offset causes measurement errors and risks damaging the microwave receiver in the network analyzer. The inadvertent DC offset is dissipated by connecting a Bias Tee device to one of the rectangular coaxial ports and shorting the DC port of the Bias Tee.

6.2 *Alignment Aids* – Material specimens must be centered in the measurement slot for accurate results. In some cases foam board, corrugated cardboard, or other specimen alignment aids may be used to center the specimen within the slot. When used, the response calibration must include the alignment aids during the calibration procedure.

6.3 *Network Analyzer*—The network analyzer must be a 2-port test set that can measure complex transmission scattering parameters.

6.4 *Response Calibration Kit*—To define the measurement reference plane and minimize fixture uncertainties, calibration of the test fixture is required. As a minimum, a response calibration procedure should be followed at the start of every measurement series. When low-dielectric centering guides are not used, the response standard is the empty fixture (clearsite). When foam-board or other similar low-dielectric materials are used to center the specimen under test, the response standard is the fixture with just the centering guides inserted.

6.5 *Full Calibration Kit*—Optionally, a through-reflect-line (TRL) or other calibration procedure that yields similar calibration quality is used to calibrate the test fixture. In the case of a TRL calibration, the calibration standards are a Thru – the empty fixture, Reflect – a shorting plate, and Line – a section of additional coaxial transmission line that is inserted.

7. Test Specimen

7.1 The test specimen must be of a width that matches the inversion database to be used to determine complex impedance. Otherwise, the inversion error will be approximately proportional to the deviation of the specimen thickness to the assumed thickness by the algorithm. The specimen must be flat when inserted into the slot, otherwise measurement error will increase, especially for lower-impedance materials.

8. Preparation of Apparatus

8.1 *Inspect Network Analyzer Test Ports*—Whenever the RF cables are reattached to the rectangular coaxial fixture, ensure that the test ports are in good working condition. Refer to network analyzer manufacturer's documentation to provide connector specifications.

8.2 *Flexing and Tightening Cables and Connectors*—Cable flexing and improperly tightened connectors introduce phase and magnitude errors into *S*-parameter data. For this reason, bend the test cables as little as possible, and under no circumstances bend the test cables smaller than the manufacturer's minimum recommended radius. Use a torque wrench with the manufacturer's recommended torque to tighten connectors.

8.3 *Network Analyzer Setup*:

8.3.1 Utilize a network analyzer that has good thermal stability. Small changes in the transmission amplitude and phase must be measured in this method. Ruggedized analyzers that do not use a cooling fan will have insufficient thermal stability for this method.

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

8.3.3 Use the network analyzer in stepped frequency mode.

8.3.4 Set the network analyzer's variable intermediate frequency (IF) bandwidth to 100 Hz or less for high fidelity measurements or up to 1000 Hz for low fidelity, faster measurements.

9. Procedure

9.1 The test procedure includes calibration and a series of specimen measurements. Note that there are two calibration procedures described: i) a mandatory response calibration and ii) an optional full calibration

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 *Full Calibration*:

9.3.1 Full calibration is a two-port calibration method that is not required, but when included, improves accuracy of the measurement method. Note that the full calibration is done using the network analyzer manufacturer's software so the exact procedure will depend on the specific analyzer used. The TRL calibration method (Thru-Reflect-Line) is used to calibration the rectangular coaxial fixture.

9.3.2 When using full calibration, the calibration coefficients will not change significantly as long as the ambient temperature is stable and the RF cables have not been changed or replaced. After the fixture is warm, a measurement of the S_{11} or S_{22} of the empty fixture is used to determine if the calibration needs to be renewed. Specifically, if the network analyzer S_{11} or S_{22} amplitude is at or below -50 dB when measuring an empty fixture, the existing calibration is sufficient and does not need to be renewed.

9.3.3 If the full calibration needs to be renewed, then a TRL calibration is performed following the network analyzer manufacturer's software and procedures.

9.4 *Response Calibration*:

9.4.1 A clearsite (empty fixture) calibration measurement is required before every measurement series. Use the following procedure to obtain the response calibration measurement.

9.4.1.1 Remove any previous sample from the fixture and ensure that there are no tools or materials within several inches of the slot opening.

9.4.1.2 When alignment aids are not used (e.g. for wider/longer rolls, with external rollers or guides), obtain the response calibration with the empty fixture by measuring S_{21}.

9.4.1.3 When alignment aids are used (e.g. for smaller sheets centered with foam board or corrugated cardboard), insert the empty alignment aids and obtain the response calibration by measuring S_{21}.

9.4.1.4 In production, when it is impractical to remove the web or paper from the device for calibraqtion it is sufficient to measure the response calibration with the neat (unprinted) web present, as long as an appropriate correction factor is applied to the data, corresponding to the known response of an unprinted web or paper.

9.4.2 *Response Calibration Frequency*—For best accuracy, repeat the calibration procedure at every 60 minutes to adjust for the effects of temperature or system drift. For any given measurement sequence, the calibration sequence must be conducted at least twice (e.g. before and after the measurements) to check for the effects of temperature or system drift.

9.5 *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.

9.6 *Specimen Measurement*:

9.6.1 When inserted into the fixture, the specimen under test must be centered within the slot as shown in FIG. 2.

9.6.2 For wider/longer specimens that use an external roller for alignment and centereing, insert the specimen into the fixture. Measure S_{21} and ratio it to the response calibration measurement. As needed, reposition the specimen for additional measurements

9.6.3 For smaller sheets that use an alignment aid, insert the specimen into the alignment aid and insert into the fixture. Measure S_{21} and ratio it to the response calibration measurement.

9.6.4 Remove the specimen and if additional specimens exist, they can be measured by repeating 9.6.1 – 9.6.3.

9.6.5 If 60 minutes or more has lapsed since the response calibration, renew the calibration.

9.6.6 Calculate the sheet impedance of the specimen(s) from the calibrated S_{21} 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,

$$S_{21}^{calibrated} = \frac{S_{21}^{specimen}}{S_{21}^{response}}$$

10.2 The complex sheet impedance, Z is then calculated from the calibrated S_{21} data. There is no analytical relationship between S_{21} and Z so a series of computational electromagnetic (CEM) model calculations must be conducted to establish this relationship. Specifically the exact geometry of the rectangular coax fixture is modeled with a full-wave finite difference time domain (FDTD) solver for a range of resistances and capacitances 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_{21} is compared to the pre-computed transmission 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 R-coax system information,
- 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 sheet impedance 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,
- 11.1.7 Calculated values of sheet impedance for the test specimen at each measurement frequency.

12. Precision and Bias

12.1 *Precision*—
- 12.1.1 The sources of precision error in complex sheet impedance measurement include:
- 12.1.1.1 Errors in measuring the magnitude and phase of the scattering parameters (i.e. VNA noise and drift)

12.2 *Bias*--

- 12.2.1 The sources of bias error in complex sheet impedance measurement include:
- 12.2.1.1 Uncertainty in the specimen dimensions,
- 12.2.1.2 Computational errors,
- 12.2.1.3 Specimen positioning/flatness errors.

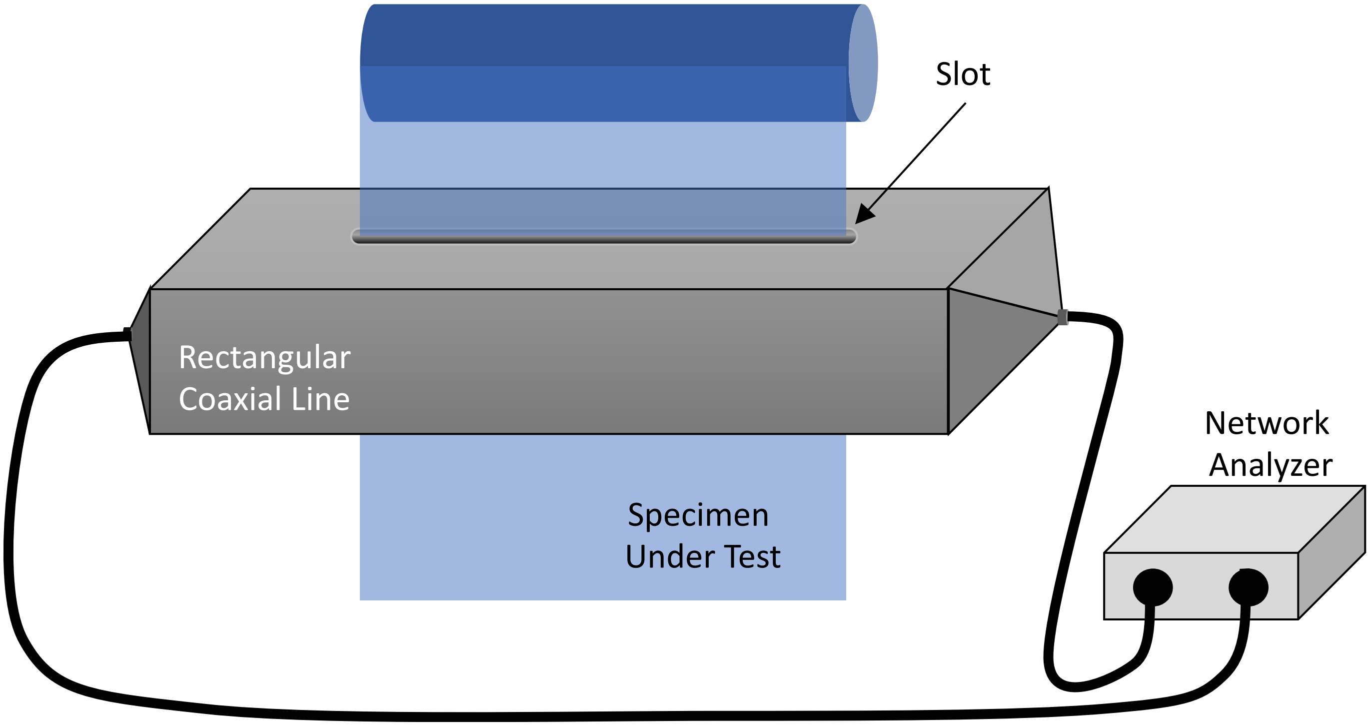

FIG. 1 Diagram of Experimental Fixture

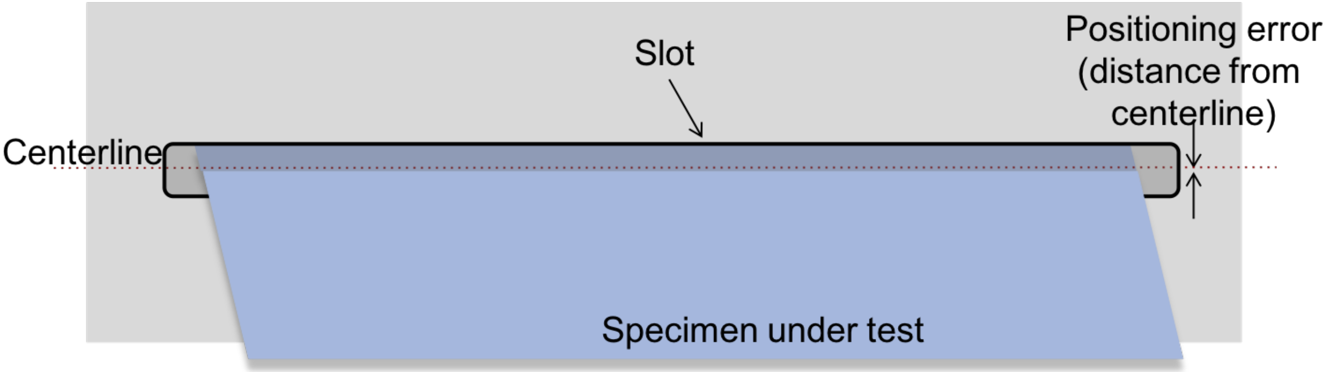

FIG. 2 Drawing of Specimen Centered in Slot

13. ANNEXES

A1. LIST OF IMPORTANT SYMBOLS

$j=\sqrt{-1}$	The complex constant
$c_0 = 2.9979\times 10^8$	Speed of light in free space (m/s)
f	Measurement frequency (Hz)
$\omega = 2\pi f$	Radian frequency (rad/sec)
$\lambda_0 = \frac{c_0}{f}$	Wavelength in free space (m)
S_{ij}	Scattering coefficient from Port j into Port i
Z	Sheet impedance
t	Thickness of electrically thin material
ρ	Resistivity