Measuring Return Loss and Electrical Thickness of Materials at Microwave Frequencies with a Free-Space Spot Probe Reflectometer

1. Scope

1.1 This test method covers a procedure for determining the return loss or thicknesses of solid materials.

1.2 This measurement method is valid over a frequency range of approximately 1 GHz to over 40 GHz. These limits are not exact and depend on the size of the specimen, the frequency range of the spot probe, and the applicable frequency range of the network analyzer used to make measurements. Being a non-resonant method, any number of discrete measurement frequencies may be selected in a measurement band.

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

2.2 US Patent 10203202B2, "Non-contact determination of coating thickness", J.W. Schultz, R.B. Schultz, J.G Maloney, K.C. Maloney, 2014

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 direction of the media is measured at a time, and therefore permittivity is a single complex number at each frequency.

3.2.2 *Relative complex permeability,* μ_r^*—the proportionality factor that relates the magnetic flux density to the magnetic field, and which depends on intrinsic material properties such as magnetic moment, domain magnetization, etc.:

$$\mu_r^* = \mu_r' - j\mu_r'' = \frac{\vec{B}}{\mu_0 \vec{H}} \qquad (2)$$

where:

μ_0= the permeability of free space,

$\vec{B}$ is the magnetic flux density vector, and

$\vec{H}$ is the magnetic field vector

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

3.2.2.2 For the purposes of this test method, only one direction of the media is measured at a time, and therefore permeability 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 measuring well-defined, standard specimens with the spot probe apparatus to characterize systematic errors. The effects of the systematic errors are then mathematically removed from the indicated measurements. The calibration also establishes the mathematical reference plane for the measurement test port.

3.3.2.1 *Discussion*—While modern vector network analyzers have this capability built in, it is also acceptable to make calibration measurements and apply the suitable calibration models as a post-processing step.

3.3.3 *Network analyzer*—a system that measures the 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 parameter (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.

3.3.5 *Time domain gate*—a mathematical procedure applied to the calibrated scattering parameter data, which minimizes coherent errors from multipath reflections.

3.3.5.1 *Discussion*—Unwanted reflections from discontinuities in the measurement fixture and from background reflections may add ripple and other systematic errors to the desired specimen scattering parameters. This procedure is equivalent to converting stepped frequency-domain data into the time-domain via Fourier transform, then applying a window function that removes all but the desired signal from the specimen. Many modern network analyzers have this function built in, but it is also acceptable to apply a time-domain gate as a post-processing step.

3.3.6 *Electrical Thickness*—the thickness of a coating or layer as determined by inversion from microwave data.

3.3.6.1 *Discussion*—In some cases, a manufacturing specification may be the thickness of a coating or layer. Since layer thickness by this method depends on having accurate permittivity or permeability data, the inverted electrical thickness may be somewhat different than the physical thickness of that layer. This happens when a layer is a composite material that includes a certain volume fraction of additive. When the additive fraction is off, the electrical thickness will then vary from physical thickness. When electrical performance is the more important criteria, then this electrical thickness is a more relevant parameter than physical thickness.

4. Executive Summary and Significance

4.1 The spot-probe apparatus, which includes the probe antenna and a vector network analyzer, is either handheld or robot mounted. It is held a known distance above the surface under test to measure the S_{11} of the test specimen. This method is similar to that of other free-space measurement methods. Calibration measurements are also made and after the data are calibrated a time-domain gate is applied.

4.2 When electrical thickness is desired, a specified data-reduction algorithm is used to calculate layer thickness. The algorithm may simultaneously solve for multiple layer thicknesses simultaneously, or may solve for one unknown layer within a known stack. Depending on the application, the surface under test may be metal-backed or air-backed.

4.3 Quality assurance for microwave and millimeter-wave components requires knowledge of material performance or thickness. This test method is useful for evaluating materials used in or applied to components. It may be used to map electromagnetic functionality or physical parameters of structural components, radomes, or absorbers.

5. Restrictions

5.1 Inversion of physical parameters such as thickness or defect detection, require measured amplitude or phase that varies in some way with frequency. Thus sufficient frequency bandwidth is needed to capture this variation and a narrow-band probe is not appropriate for this method.

5.2 Layer thickness inversion treats the thickness as a free variable with the assumption that the permittivity and permeability of the material(s) are known. Thus incorrect permittivity and permeability data can prevent determination of proper thicknesses.

5.3 In contrast to a focused beam system, spot probe illumination contains a broader spectrum of plane wave content. For this reason, small aperture spot probes are not appropriate for oblique angle measurements unless there is some sort of lens or other focusing element also employed.

6. Apparatus

6.1 *Experimental Test Fixture*— The test apparatus includes a spot probe antenna combined with a vector network analyzer connected to the probe with a short coaxial transmission line, as shown in Fig. 1. The probe is held a set distance away from the measurement surface under test.

6.1.1 *Robot Mounted*—When mounted on a robotic arm, the robot system is used to position the probe with a repeatability of better than +/- 0.1 inch (+/- 2.5 mm) relative to the surface under test. The positioning must also be normal to the surface tangent with a repeatability of no more than +/- 5 degrees.

6.1.2 *Handheld*—When used in a handheld apparatus, a low-dielectric spacer is mounted on the end of the spot probe to maintatin the necessary position and angle repeatability.

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. Long RF cables must not be used as they add measurement uncertainty from thermal drift and flex.

6.3 *Calibration Kit*— To define the measurement reference plane and minimize apparatus uncertainties, calibration of the test fixture is required. As a minimum, a response and isolation calibration procedure should be followed. The reflection response standard is a flat metal plate, of no less than 6 mm thickness (so it does not flex), with a machined or polished surface finish. The metal plate is preferably 30 cm x 30 cm. The isolation response standard is simply an open space clear of any electronics or materials (clearsite).

7. Test Specimen

7.1 Ensure that the lateral dimensions of the surface under test (orthogonal to the thickness direction) are larger than the illuminating beam. The amplitude of the incident beam must be -20 dB or less at the edges of the sample, relative to the beam center. Similarly for a large surface, the probe must be positioned a sufficient distance from the edge of the specimen so that edge diffraction does not cause too much ripple. In the case of being near a a single edge, it is sufficient for the power on that edge to be no greater than -10 dB relative to the peak.

7.2 When layer thickness is inverted, estimated or previously measured intrinsic properties (permittivity and permeability) must be known.

8. Preparation of Apparatus

8.1 *Inspect Network Analyzer Test Ports*— When first assembling the probe onto the networ analyzer, ensure that the test ports are in good working condition. Refer to network analyzer manufacturer's documentation to provide connector specifications.

8.2 *Tightening Connectors*— Improperly tightened connectors introduce phase and magnitude errors into *S*-parameter data. For this reason, tighten the RF connectors between the probe antenna and the network analyzer with sufficient torque. During regular use, check the RF connectors between the probe antenna and network analyzer at least once a week to ensure they have not loosened over time.

8.3 *Network Analyzer Setup*:

8.3.1 Refer to manufacturer documentation for minimum warm-up period for the network analyzer (typically 30 minutes). When the internal temperature of the analyzer can be monitored, it alternatively is used to determine when the system is sufficiently warm. After initial power-up, the apparatus is considered 'warmed-up' once the analyzer temperature drift is at or below 0.2 degrees C per minute. After the initial warm-up, recalibration is required only when the measured analyzer temperature changes by 5 degree C or more.

8.3.2 Use the network analyzer in stepped frequency mode. Set the start frequency and stop frequency as desired. Set the number of measurement points to ensure an unambiguous range of at least 7 or 8 meters to ensure background reflections can be properly resolved. The unambiguous range can be estimated by $R_{unambiguous} = cN/(f_{max} - f_{min})$, where N is the number of frequency steps, c is the speed of light, and $f_{min/max}$ are the measured frequency limits. For example, the use of 401 points over a frequency span of 2 to 18 GHz corresponds to an unambiguous range of ~7.5 meters (~25 feet), which is sufficient for this method. When measurement speed considerations allow, a higher number of points (e.g. 801) is used to improve gating accuracy.

8.3.3 Set the network analyzer's variable intermediate frequency (IF) bandwidth to 3000 Hz or less.

9. Procedure

9.1 The test procedure includes calibration and a series of specimen measurements.

9.2 *Calibration*:

9.2.1 Two calibration standards are required: a metal plate that is smooth and flat, and a clearsite (no specimen).

9.2.2 Use the following procedure to obtain the response (R_{ij}) and isolation (I_{ij}) calibration parameters for the S_{11} scattering parameter:

9.2.2.1 Aim the probe at the metal plate standard and measure S_{11} (R_{11}) to obtain reflection response coefficients versus frequency. Make sure the probe is positioned with a known distance to the plate (typically about two inches) and that it is oriented normal to the plate's surface. It is important that the probe to metal plate distance be the same as the probe distance for the surface(s) under test, to within +/-2.5 mm or better.

9.2.2.2 Aim the probe away from the metal plate and towards free space (with no nearby objects within 30 cm or more of the probe) and obtain the reflection isolation coefficient (I_{11}).

9.2.3 *Calibration Frequency*—For a series of specimen measurements, repeat the calibration procedure at least every 2 to three hours, or whenever the temperature drift of the network analyzer is more than 5 degrees C, whichever is sooner.

9.2.4 *Calibration Validation*--For any given measurement sequence, the calibration sequence must be conducted at least twice to check for loose RF connectors or other spurious problems. This calibration validation must be done either twice before the measurement sequence, or once before and again afterwords.

9.2.5 *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.

9.3 *Specimen Measurement*:

9.3.1 Position the spot probe over the surface to be measured and collect S_{11} data.

9.3.2 If mapping a surface, reposition the probe to each location desired and repeat 9.3.1

9.3.3 If the thermal drift of the network analyzer has exceeded 5 degrees C, renew the calibration

9.3.4 Apply the calibration data to the specimen measurements, apply time domain gating, and calculate the layer thickness or other desired properties of the surface from the calibrated scattering parameters, as described in the following Calculation section.

10. Calculation

10.1 The calibrated scattering parameters for a given specimen are obtained from the calibration parameters by,

$$S_{ij}^{calibrated} = \frac{S_{ij}^{measured} - I_{ij}}{R_{ij} - I_{ij}} \quad (5)$$

where *ij* is the 11 scattering parameter.

10.2 Time domain gating must be applied to the calibrated scattering parameters to further reduce errors. Specifically, gating ensures that multipath reflections within the spot probes do not bias the desired reflection and transmission coefficient of the specimen under test. For 2-18 GHz measurements, a 0.5 ns width gate is typical. For other frequency ranges or other specimen types, different time domain settings will be appropriate. If necessary, check that the gate window width fully encompasses the measured specimen signal by viewing the frequency data in time domain. Note that increasing the width of the gate may allow unwanted multipath from the probe 'ring-down' to add ripple to the measured signal.

10.3 *N-layer inversion*—Calculating electrical thickness from the measured S_{11} requires an iterative algorithm to match the measured data to a transmission line model of the single or multilayer structure of the surface under test. The model is constructed by realizing each material layer as an "R-matrix" calculated by,

$$R = \frac{1}{T(1-\Gamma^2)}\begin{bmatrix} T^2-\Gamma^2 & \Gamma-\Gamma T^2 \\ \Gamma T^2-\Gamma & 1-\Gamma^2T^2 \end{bmatrix} \quad (6)$$

where $\Gamma = \frac{\mu_r^* - \sqrt{\mu_r^*\varepsilon_r^*}}{\mu_r^* + \sqrt{\mu_r^*\varepsilon_r^*}}$, $T = e^{-\gamma t}$, $\gamma = \sqrt{-\mu_r^*\varepsilon_r^* k_0^2}$, and k_0 is the wavenumber in air (= $2\pi/\lambda_0$). In these equations, μ_r^* and ε_r^* are the relative complex permeability and permittivity of the layer and t is the layer thickness. Multiple layers can be constructed by determining the R-matrix for each layer and then cascading them together in a matrix-multiply operation,

$$R_{total} = R_1 R_2 R_3 \ldots \quad (7)$$

This R-matrix is then converted to scattering parameters and specifically the reflection scattering parameter is calculated as $S_{11} = R_{12}/R_{22}$, where R in this case are the matrix elements of the R-matrix of equations (6) and (7). These equations are then iteratively compared to the measured S_{11} using standard interative methods such as Nelder-Mead and/or Genetic Optimization. To obtain layer thickness(es), t for each unknown layer are treated as a variables and the iteration minimizes the difference between the model and measured S_{11} by varying these layer thicknesses. Additional details on this algorithm are provided in the referenced documents.

11. Report

11.1 Report the following information:

11.1.1 Operator name, time and date of measurement,

11.1.2 Spot probe system information,

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

11.1.4 Model parameters (number and construction/properties of layers),

11.1.5 Calculated values of the verification specimen at each measurement frequency,

11.1.6 Test specimen identification and origin,

11.1.7 Specimen radius of curvature, and

11.1.8 Calculated values for the test specimen at each measurement frequency.

12. Precision and Bias

12.1 *Precision*—It is not practicable to specify the precision of the procedure in this test method because of the multiple variables that influence precision. In specific measurements, it is possible to estimate measurement precision by estimating the uncertainties of the measured scattering parameters and probe alignment, and then applying a differential analysis or Monte-Carlo simulations to the given equations.

12.2 The sources of error in permeability and permittivity measurement include:

12.2.1.1 Errors in measuring the magnitude and phase of the scattering parameters,

12.2.1.2 Uncertainty in probe – surface distance and angle,

12.2.1.3 Line losses and connector mismatch,

12.2.1.4 Focusing/plane-wave errors[1],

12.3 *Bias*—Bias of the procedure in this test method can occur if the sample has significant curvature. When that curvature is concave, the measured amplitude will be higher and when that curvature is convex the measured amplitude will be lower across the measured frequency band. This bias is corrected for by including a curvature correction in the iterative solver. In this case, a measured or pre-calculated table is used to apply curvature correction based on the known radius of curvature. Alternatively for metal backed applications, a robotic system can use the spot probe to conduct a baseline measurement of the component under test and the deviations from ideal reflectivity are used to determine the curvature correction. If necessary, curvature correction is included as a fitted parameter in the inversion algorihm.

[1] L.E.R. Petersson, G.S. Smith, "An estimate of the error caused by the plane-wave approximation in free-space dielectric measurement systems," IEEE Trans. AP, 50(6), 878-887, June 2002

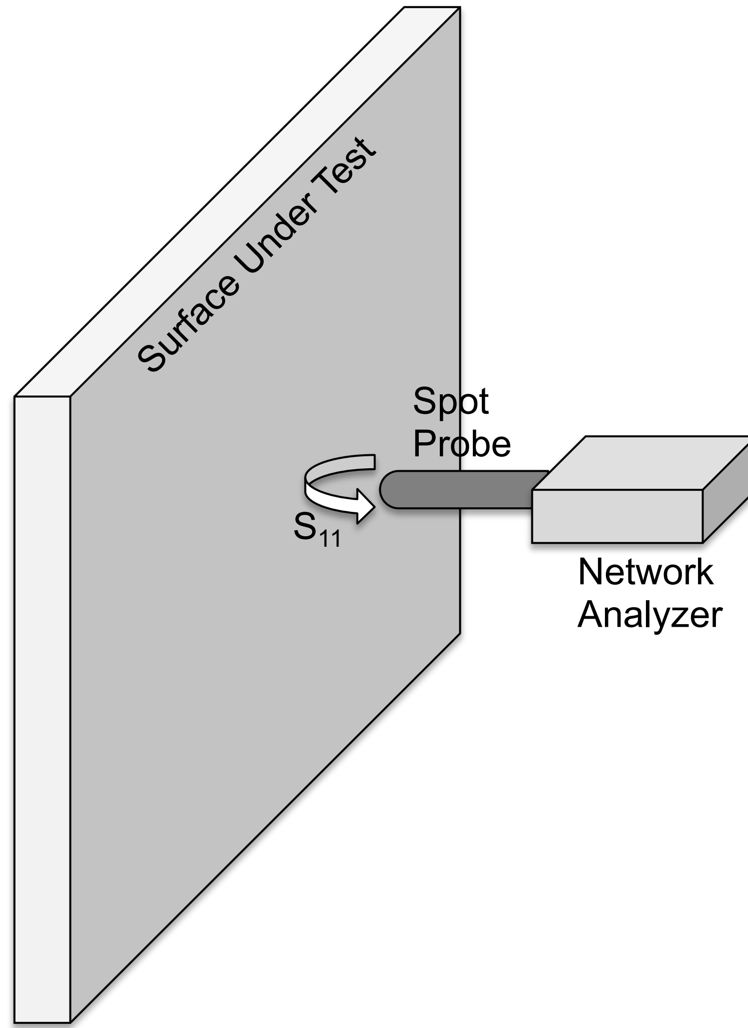

FIG. 1 Diagram of Experimental Fixture

13. ANNEXES

A1. LIST OF IMPORTANT SYMBOLS

$j=\sqrt{-1}$	The complex constant
$c_0=2.9979\times10^8$	Speed of light in free space (m/s)
$\varepsilon_0=8.854\times10^{-12}$	Permittivity of free space (Farads/m)
$\mu_0=4\pi\times10^{-7}$	Permeability of free space (Henrys/m)
f	Measurement frequency (Hz)
$\omega=2\pi f$	Radian frequency (rad/sec)
$\lambda_0=\frac{c_0}{f}$	Wavelength in free space (m)
$\varepsilon_r^*=\varepsilon_r^{'}-j\varepsilon_r^{''}$	Relative complex permittivity of specimen
$\mu_r^*=\mu_r^{'}-j\mu_r^{''}$	Relative complex permeability of specimen
S_{ij}	Scattering coefficient from Port j into Port i
R_{ij}	Response calibration scattering coefficient from Port j into Port i
I_{ij}	Isolation calibration scattering coefficient from Port j into Port i
t	Specimen thickness (m)
$k_o=\frac{2\pi}{\lambda_0}$	Wavenumber in free space (rad/m)
$\gamma_0=\sqrt{-k_0^2}$	Propagation constant in free space (rad/m)
$\gamma=\sqrt{-\mu_r^*\varepsilon_r^*k_0^2}$	Propagation constant in specimen (rad/m)
Γ	Reflection coefficient at specimen/air interface
T	Transmission coefficient through specimen

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