Measuring Shielding Effectiveness of Materials at Microwave Frequencies with a Free-Space Focused Beam

1. Scope

1.1 This test method covers a procedure for determining the shielding effectiveness of sheet materials.

1.2 This measurement method is valid over a frequency range of approximately 1 GHz to over 100 GHz. These limits are not exact and depend on the size of the specimen, the design of the lenses, the frequency range of the feed horns, and on the applicable frequency range of the network analyzer used to make measurements. The practical lower frequency is limited by specimen dimension and fixturing requirements (large specimens and/or fixturing at low frequencies). 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

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 *Shielding Effectiveness, SE*—a measure of the electromagnetic power blocked by a specimen in dB, computed from the square of the ratio of incident field relative to transmitted field:

$$\boldsymbol{SE = 10\log_{10}\left|\frac{\vec{E_i}}{\vec{E_t}}\right|^2 = -20\log_{10}|S_{21}|} \qquad (1)$$

where

$\vec{E_t}$ = the electric field vector after transmission through the specimen and

$\vec{E_i}$ = the electric field vector incident on the specimen and

S_{21} = the complex Port 1 to Port 2 transmission scattering parameter.

3.2.1.1 *Discussion*— This definition assumes a free-space wave incident on a sheet of material. In general, shielding effectiveness increases as conductivity increases with the smallest possible *SE* being 0 for no material and the largest possible SE being infinite for an infinitely large perfect electric conductor. Shielding effectiveness is synonymous with insertion loss. For anisotropic specimens, shielding effectiveness is polarization dependent and described by a tensor.

3.2.1.2 For the purposes of this test method, only specimens of planar geometry are considered and only one tensor component of the media is measured at a time, and therefore *SE* is a single scalar 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 inserting well-defined, standard specimens into the focused beam fixture to characterize the measurement system's systematic errors. The effects of the systematic errors are then mathematically removed from the indicated measurements.

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 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) in the forward and/or reverse directions of a two-port network (S_{11}, S_{21}, S_{12}, S_{22}).

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*—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.

3.3.4.2 The shielding effectiveness is determined directly from the transmission S-parameters, S_{21} or S_{12}.

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 or stray radiation interacting with the surroundings 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.

4. Executive Summary and Significance

4.1 A planar test specimen is placed in a focused beam test fixture, which consists of two horn and lens pairs connected to a network analyzer. Depending on the size of the specimen and spot size of the focused beam, it is acceptable to mount the sample in a metal aperture wall to reduce leakage around the specimen. This test fixture is used to measure the S-parameters of the test specimen, along with appropriate calibration standards. After the data are calibrated, a time-domain gate is applied, and the shielding effectiveness is calculated from the Port 1 to Port 2 transmission S-parameter magnitude.

4.2 Designs for microwave and millimeter-wave components require the knowledge of shielding effectiveness of applicable materials at operating frequencies. This test method is useful for evaluating experimental batch or continuous production materials used in these electromagnetic applications.

5. Restrictions

5.1 Excessive attenuation, insufficient dynamic range of the network analyzer, and high conductivity of the specimen can prevent accurate determination of shielding effectiveness. Use of apertures, reducing network analyzer intermediate frequency channel bandwidth, and increasing number of measurement points of the network analyzer can improve measurement accuracy by reducing noise in the time gate window.

5.2 Aperture wall shielding effectiveness should be greater than the specimen when the aperture is blocked by the isolation calibration standard.

5.3 Specimens should make good electrical contact with aperture edge(s) to prevent leakage.

6. Apparatus

6.1 *Experimental Test Fixture*— The test fixture includes two collinearly aligned pairs of feed antennas and lenses, a specimen holder, and a network analyzer, as shown in Figure 1. When specimen dimensions are too small to prevent leakage around the material, an aperture wall is also included as shown in Figure 2. The specimen holder or aperture wall is placed at the focal plane between the lenses to ensure a minimum amplitude taper. If reflections from nearby surroundings interfere with the measured signal, those surroundings must be adjusted, or microwave absorber used to attenuate the multipath reflections.

6.2 *Network Analyzer*— The network analyzer must have a two-port test set that can measure the complex transmission scattering parameter from Port 1 to Port 2.

6.3 *Calibration Kit*— To minimize fixture uncertainties, calibration of the test fixture is required. As a minimum, a response and isolation calibration procedure should be followed. The transmission isolation standard is a flat metal plate, preferably the same size as the specimen. The transmission response standard is the empty test fixture (clearsite).

6.4 *Lens Design*:

6.4.1 The test fixture includes two identical focusing lenses, manufactured from a well-characterized dielectric material. The transmit lens accepts radiation from the feed antenna and focuses it onto the test specimen. The receive lens transfers the radiation transmitted through the specimen into the receive antenna. The lenses must have a low to moderate dielectric permittivity to minimize multipath reflections, while still providing the necessary focusing power. The lens material permittivity should also be approximately constant across the measurement frequency range.

6.4.2 For this measurement method, the lens specification is defined in terms of two performance characteristics: beam waist and phase taper. Both of these performance characteristics are evaluated at the lens focal point (specimen position). Verification of lens performance characteristics is performed by scanned probe measurements of the focus position or by an inverse synthetic aperture (ISAR) method with a rotated metal plate.

6.4.3 The beam waist, w_0, is the radius of the beam at the focal point where the amplitude is reduced by 8.7 dB relative to the center of the beam. This corresponds to the radius where the field is reduced by a factor of 1/*e*, where *e* = 2.7183. In wavelength scaled units, the waist is given by

$$k_0 w_0 = \frac{2\pi w_0}{\lambda_0}. \qquad (3)$$

6.4.3.1 The lens is designed to achieve two goals: i) minimize the beam waist so that specimen size can be minimized and ii) approximate a plane wave by minimizing phase taper within the beam. However, a beam waist that is too small results in excessive focusing errors caused by deviation from ideal plane wave behavior. For reasonable accuracy with most materials the beam waist must be no less than $k_0w_0 = 6$. In non-symmetrical beams where the cross-section is more accurately described as elliptical, the minimum beam waist specification applies to the smallest dimension of the beam.

6.4.3.2 The phase taper of the focus position also affects measurement accuracy and deviation from a plane wave behavior (no phase taper) must be minimized. In the focused beam measurement system, phase taper within the beam waist region must be no more than +/- 15 deg.

6.5 *Aperture Wall*— For samples of insufficient size to prevent leakage around the material, an aperture wall is used to block that leakage as shown in Figure 2. The size of the aperture wall must be large enough to put the slant path from the source antenna to the wall edge so that it is outside of the time domain window. For example, if the horn-to-specimen direct path distance is 1.3 meters and a 0.5 ns time domain window is used, the width of the aperture wall should be approximately 2 meters or more to ensure that the slant path is long enough for sidelobe leakage to be well outside of the time domain window[1].

7. Test Specimen

7.1 Specimen thickness must be less than the focal depth, z_R, of the beam[2],

$$\boldsymbol{z_R} < \frac{\boldsymbol{\pi w_0^2}}{\boldsymbol{\lambda}}. \qquad (4)$$

7.1 Ensure that the lateral specimen dimensions (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 edge of the sample, relative to the beam center.

7.2 Shielding effectiveness of the specimen should be 15 dB higher than the noise floor of the test fixture for accurate characterization of the specimen. The noise floor is measured with a solid metal plate as the specimen.

8. Preparation of Apparatus

8.1 *Inspect Network Analyzer Test Ports*—Insure 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 *System Alignment*—The feed horns, lenses, and specimen holder must be aligned so that they are all centered along a common line. Additionally, the planes that define the aperture of horns, lenses and specimen holder must all be aligned orthogonally to that common line. Alignment is established geometrically (through careful positioning of each of these elements).

8.4 *Network Analyzer Setup*:

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

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[1] Note the direct path includes extra effective path length due to the slightly slower speed of light going through the thickness of the lens

[2] Defined by the Rayleigh Length in Gaussian Beam theory

8.4.2 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 twice the path length between the two network analyzer ports. Ignoring the effects of dielectric in the RF cables, the unambiguous range is 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. If noise from room reflections are aliased into the time gate window, increase the unambiguous range beyond twice the path length to reduce this noise.

8.4.3 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 on both sides, and a clear site (no specimen).

9.2.2 Use the following procedure to obtain the response (R_{ij}) and isolation (I_{ij}) calibration parameters for Port 1 to Port 2 transmission scattering parameter (S_{21}):

9.2.2.1 Measure S_{21} with no specimen to obtain the transmission response (R_{21}).

9.2.2.2 Insert the metal plate standard and measure S_{21} to obtain the transmission isolation (I_{21}).

9.2.3 *Calibration Frequency*—For a series of specimen measurements, repeat the calibration procedure at least every 90 minutes to check 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.

9.2.4 *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.

9.3 *Specimen Measurement*:

9.3.1 Insert the specimen into the sample holder and collect the Port 1 to Port 2 scattering parameter with the network analyzer. For typical focused beam fixtures, the sample front face should be within a few millimeters of the reference plane established by the metal plate calibration to ensure it is within the focal depth, z_R, of the beam.

9.3.2 Remove the specimen and if additional specimens exist, they can be measured by repeating 9.3.1.

9.3.3 If 90 minutes or more has lapsed since the calibration, renew the calibration.

9.3.4 Apply the calibration data to the specimen measurements, apply time domain gating, and compute the shielding effectiveness.

10. Calculation

10.1 The calibrated Port 1 to Port 2 transmission scattering parameter for a given specimen is obtained from the calibration parameters by,

$$\boldsymbol{S_{21}^{calibrated} = \frac{S_{21}^{measured} - I_{21}}{R_{21} - I_{21}}} \qquad (5)$$

10.2 Time domain gating must be applied to the calibrated scattering parameter to further reduce errors. For 2-20 GHz measurements, a 0.5 to 1.0 ns width is typical. For other frequency ranges or other specimen types, different time domain settings will be appropriate. Check that the gate window width fully encompasses the measured specimen signal by viewing the frequency data in time domain.

10.3 Multiply the magnitude of the Port 1 to Port 2 transmission scattering parameter in decibels by -1 to obtain the shielding effectiveness (insertion loss) of the specimen.

11. Report

11.1 Report the following information:

11.1.1 Operator name, time and date of measurement,

11.1.2 Focused beam system information,

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

11.1.4 Calculated values of the shielding effectiveness at each frequency,

11.1.5 Test specimen identification and origin,
11.1.6 Specimen dimensions and uncertainties used in data reduction, and
11.1.7 Specimen flatness.

12. Precision and Bias

12.1 *Precision*—It is not practicable to specify the precision of the procedure in this test method for measuring shielding effectiveness 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 specimen dimensions, and then applying a differential analysis to the given equations.[3]

12.2 The sources of error in shielding effectiveness measurement include:

12.2.1.1 Errors in measuring the magnitude and phase of the scattering parameters,
12.2.1.2 Line losses and connector mismatch,
12.2.1.3 Focusing errors[3], and
12.2.1.4 Alignment errors.

12.3 *Bias*—Bias of the procedure in this test method can occur if the sample is over-illuminated. Over-illumination results in edge diffraction and increased transmission around the sample. This bias is minimized when the power density of the illuminating beam at the sample edge is no more than -20 dB relative to the peak. Thus, for a typical, $k_0w_0 = 8$ beam, the lateral dimensions of the specimen should be no smaller than 6 wavelengths across. Additionally, this bias is minimized when an aperture wall is used to prevent leakage around the specimen.

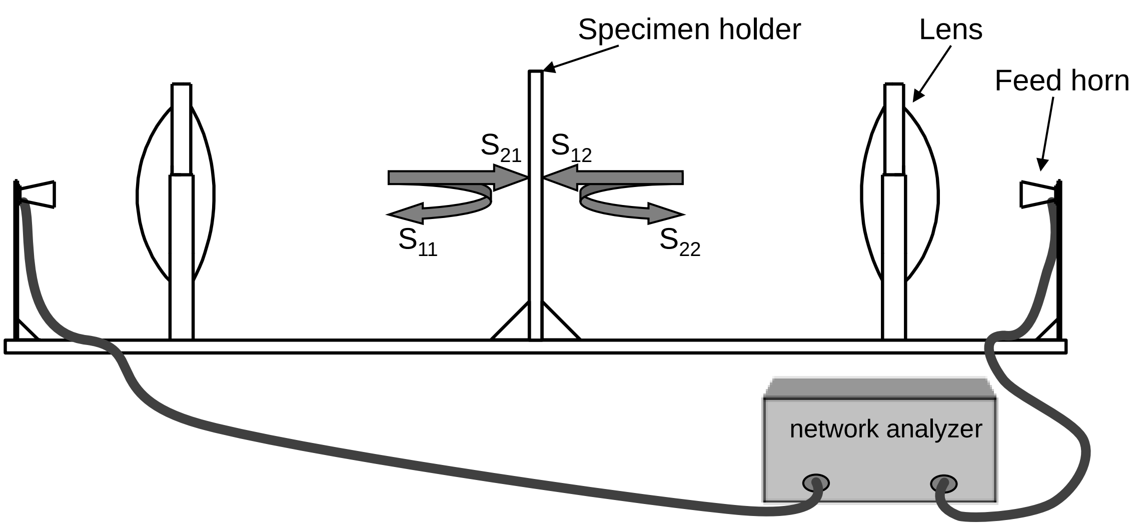

Figure 1: Diagram of the Focused Beam Test Fixture

[3] 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

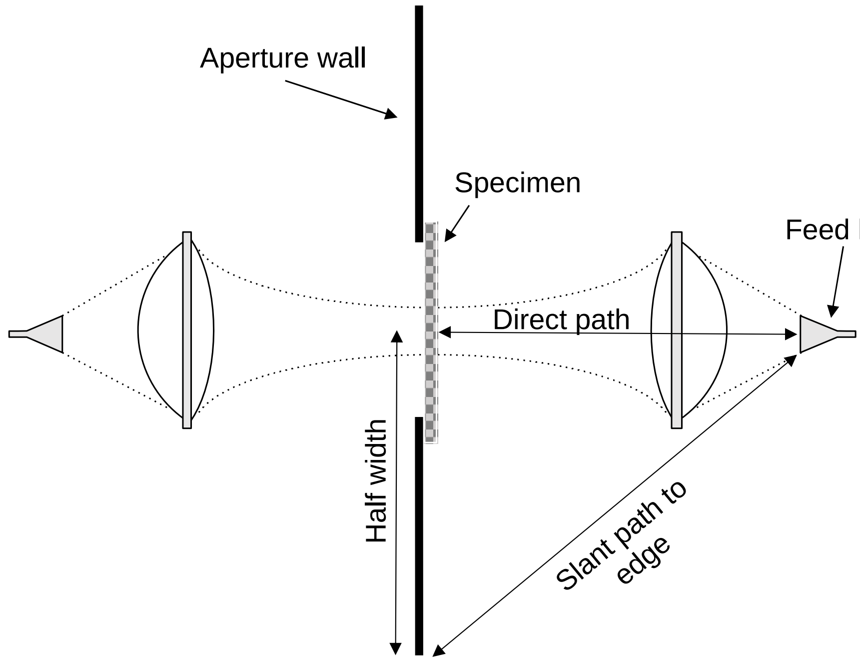

Figure 2: Diagram of aperture wall with focused beam system

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)
SE	Shielding effectiveness of the 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
w_o	Waist of focused beam (at focal point) (m)
t_m	Metal calibration plate thickness (m)
$k_o = \frac{2\pi}{\lambda_0}$	Wavenumber in free space (rad/m)
$z_R = \frac{\pi w_0^2}{\lambda}$	Focal depth of focused beam (m)