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Standard Test Method for Measuring Relative Complex Permittivity and Relative Magnetic Permeability of Solid Materials at Microwave Frequencies Using Coaxial Air Line[1]

This standard is issued under the fixed designation D7449/D7449M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε^1 NOTE—Equation 5 was editorially updated in March 2012.

1. Scope

1.1 This test method covers a procedure for determining relative complex permittivity (relative dielectric constant and loss) and relative magnetic permeability of isotropic, reciprocal (non-gyromagnetic) solid materials. If the material is nonmagnetic, it is acceptable to use this procedure to measure permittivity only.

1.2 This measurement method is valid over a frequency range of approximately 1 MHz to over 20 GHz. These limits are not exact and depend on the size of the specimen, the size of coaxial air line used as a specimen holder, and on the applicable frequency range of the network analyzer used to make measurements. The practical lower and upper frequencies are limited by specimen dimension requirements (large, thick specimens at low frequencies and small specimens at high frequencies). For a given air line size, the upper frequency is also limited by the onset of higher order modes that invalidate the dominant-mode transmission line model and the lower frequency is limited by the smallest measurable phase shift through a specimen. Being a non-resonant method, the selection of any number of discrete measurement frequencies in a measurement band would be suitable. The coaxial fixture is preferred over rectangular waveguide fixtures when broadband data are desired with a single sample or when only small sample volumes are available, particularly for lower frequency measurements

1.3 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard. 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 *ASTM Standards:*[2]

D1711 Terminology Relating to Electrical Insulation

3. Terminology

3.1 For definitions of terms used in this test method, refer to Terminology D1711.

3.2 *Definitions:*

3.2.1 *relative complex permittivity (relative complex dielectric constant),* ε_r^*, *n*—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.:

$$\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r'' = \frac{\vec{D}}{\varepsilon_0 \vec{E}} \tag{1}$$

where:

ε_0 = permittivity of free space

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

$\vec{E}$ = 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

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

part of complex relative permittivity (ε_r'') is often referred to as the loss factor. In anisotropic media, permittivity is described by a three dimensional tensor. For the purposes of this test method, the media is considered to be isotropic, and therefore permittivity is a single complex number at each frequency.

3.2.2 *relative complex permeability,* μ_r^*, *n*—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.:

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

where:

μ_0 = permeability of free space

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

$\vec{H}$ = 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 described by a three dimensional tensor. For the purposes of this test method, the media is considered to be isotropic, 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, n*—a procedure for connecting characterized standard devices to the test ports of a network analyzer to characterize the measurement system's 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 ports.

3.3.2.1 *Discussion*—Modern network analyzers have this capability built in. There are a variety of calibration kits that can be used depending on the type of test port. The models used to predict the measurement response of the calibration devices depends on the type of calibration kit. Most calibration kits come with media that can be used to load the definitions of the calibration devices into the network analyzer. Calibration kit definitions loaded into the network analyzer must match the devices used to calibrate. Since both transmission and reflection measurements are used in this standard, a two-port calibration is required.

3.3.3 *cutoff frequency, n*—the lowest frequency at which non-evanescent, higher-order mode propagation can occur within a coaxial transmission line

3.3.4 *network analyzer, n*—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.

3.3.4.1 *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 reverse directions of a two-port network (S_{11}, S_{21}, S_{12}, S_{22}).

3.3.5 *scattering parameter (S-parameter),* S_{ij}, *n*—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.

3.3.5.1 *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 transmitted wave voltage at Reference Plane 2 (Port 2) divided by the incident wave voltage measured at Reference Plane 1 (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 at reference plane 1 (Port 1).

3.3.6 *transverse electromagneticc (TEM) wave, n*—an electromagnetic wave in which both the electric and magnetic fields are everywhere perpendicular to the direction of propagation.

3.3.6.1 *Discussion*—In coaxial transmission lines the dominant wave is TEM.

4. Summary of Test Method

4.1 A carefully machined test specimen is placed in a coaxial air line and connected to a calibrated network analyzer that is used to measure the *S*-parameters of the transmission line-with-specimen. A specified data-reduction algorithm is then used to calculate permittivity and permeability. If the material is nonmagnetic, a different algorithm is used to calculate permittivity only. Error corrections are then applied to compensate for air gaps between the specimen and the transmission line conductor surfaces.

5. Significance and Use

5.1 Design calculations for radio frequency (RF), microwave and millimetre-wave components require the knowledge of values of complex permittivity and permeability at operating frequencies. This test method is useful for evaluating small experimental batch or continuous production materials used in electromagnetic applications. Use this method to determine complex permittivity only (in non-magnetic materials) or both complex permittivity and permeability simultaneously.

6. Interferences

6.1 The upper limits of permittivity and permeability that can be measured using this test method are restricted by the transmission line and specimen geometries, which can lead to unwanted higher order waveguide modes. In addition, excessive electromagnetic attenuation due to a high loss factor within the test specimen can prevent determination of permittivity and permeability. No specific limits are given in this standard, but this test method is practically limited to low-to-medium values of permittivity and permeability.