Designation: ~~D2520 – 13~~ D2520 – 21

Standard Test Methods for Complex Permittivity (Dielectric Constant) of Solid Electrical Insulating Materials at Microwave Frequencies and Temperatures to ~~1650°C~~1650 °C[1]

This standard is issued under the fixed designation D2520; 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.

1. Scope

1.1 These test methods cover the determination of relative (Note 1) complex permittivity (dielectric constant and dissipation factor) of nonmagnetic solid dielectric materials.

NOTE 1—The word "relative" is often omitted.

1.1.1 *Test Method A* is for specimens precisely formed to the inside dimension of a waveguide.

1.1.2 *Test Method B* is for specimens of specified geometry that occupy a very small portion of the space inside a resonant cavity.

1.1.3 *Test Method C* uses a resonant cavity with fewer restrictions on specimen size, geometry, and placement than Test Methods A and B.

1.2 Although these test methods are used over the microwave frequency spectrum from around 0.5 to 50.0 GHz, each octave increase usually requires a different generator and a smaller test waveguide or resonant cavity.

1.3 Tests at elevated temperatures are made using special high-temperature waveguide and resonant cavities.

1.4 The values stated in SI units are to be regarded as standard. The values given in parentheses after SI units are inch-pound units that are provided for information only and are not considered standard.

1.5 *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~~ safety, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

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[1] These test methods are under the jurisdiction of ASTM Committee D09 on Electrical and Electronic Insulating Materials and is the direct responsibility of Subcommittee D09.12 on Electrical Tests.

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2. Referenced Documents

2.1 *ASTM Standards:*[2]

A893/A893M Test Method for Complex Dielectric Constant of Nonmetallic Magnetic Materials at Microwave Frequencies
D150 Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation
D1711 Terminology Relating to Electrical Insulation

3. Terminology

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

3.1 *Definitions:*

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

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *neper, n*—a division of the logarithmic scale wherein the number of nepers is equal to the natural logarithm of the scalar ratio of either two voltages or two currents.

NOTE 2—The neper is a dimensionless unit. 1 neper equals 0.8686 bel. With I_x and I_y denoting the scalar values of two currents and *n* being the number of nepers denoted by their scalar ratio, then:

$$n = ln_e(l_x/l_y)$$

where:

ln_e = logarithm to base e.

~~3.2.2 For other definitions used in these test methods, refer to Terminology D1711.~~

3.3 *Definitions of Terms Specific to Test Methods B and C:*

3.3.1 *electrical skin depth, n*—the effective depth of field penetration at high frequencies where electric currents are confined to a thin layer at the surface of conductors due to basic electromagnetic phenomena.

3.3.1.1 *Discussion*—

The skin depth for copper and silver is approximately 0.002 mm at 1 GHz and decreases by a factor of 10 at 100 GHz.

3.3.2 *high Q cavity, n*—a rectangular cavity having a *Q* greater than 2000.

3.3.2.1 *Discussion*—

Q defines the bandwidth (or sharpness) of the resonance curve of field intensity plotted against frequency. *Q* is the reciprocal of the electrical loss with a high *Q* indicating low electrical losses of the cavity and dielectrics and is obtained by optimum choice of cavity dimensions, use of high conductivity metals (such as silver and copper) with highly polished surfaces (that is, surface roughness much smaller than electrical skin depth at the test frequency). High *Q* is enhanced by choice of large cavity volume to surface area. Surface irregularities or variations in flatness, radius of curvature, or parallelism of walls, leads to spurious resonance modes which introduce electrical losses and lower the cavity *Q*.

3.3.3 *microwave, adj*—referring to electromagnetic wavelengths of 30 cm or less where the corresponding frequency is 1 GHz or higher.

3.3.4 *resonant cavity, n*—an enclosure with conducting walls which will support electromagnetic resonance of various specific modes dependent on the cavity geometry and dimensions, and on the integral number of half waves and their directions of propagation as terminated by the cavity walls.

3.3.4.1 *Discussion*—

In practice, allowance must be made for input and output coupling holes, probes, or loops. Openings or means of disassembling must be provided for introducing dielectric specimens.

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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.

4. Significance and Use

4.1 Design calculations for such components as transmission lines, antennas, radomes, resonators, phase shifters, etc., require knowledge of values of complex permittivity at operating frequencies. The related microwave measurements substitute distributed field techniques for low-frequency lumped-circuit impedance techniques.

4.2 Further information on the significance of permittivity is contained in Test Methods D150.

4.3 These test methods are useful for specification acceptance, service evaluation, manufacturing control, and research and development of ceramics, glasses, and organic dielectric materials.

TEST METHOD A—SHORTED TRANSMISSION LINE METHOD

5. Scope

5.1 This test method covers the determination of microwave dielectric properties of nonmagnetic isotropic solid dielectric materials in a shorted transmission line method. This test method is useful over a wide range of values of permittivity and loss (**1**).[3] It is suitable for use at any frequency where suitable transmission lines and measuring equipment are available. Transmission lines capable of withstanding temperatures up to ~~1650°C~~1650 °C in an oxidizing atmosphere can be used to hold the specimen.

6. Summary of Test Method

6.1 ~~For an isotropic dielectric medium, one of Maxwell's curl equations is written~~

~~$\text{curl } H = j\omega\kappa^*\varepsilon_0 E$ (1)~~

~~assuming exp~~For an ~~(jωt)~~isotropic ~~time dependence,~~dielectric medium, one of Maxwell's curl equations is written:

$$\text{curl } H = j\omega\kappa^*\varepsilon_0 E \tag{1}$$

assuming exp *(jωt)* time dependence, where:

κ^* = relative complex permittivity,
ε_0 = (absolute) permittivity of free space, and
ω = $2\pi f$, f being the frequency.

The notation used will be as follows:

$$\kappa^* = \kappa' - j\kappa'' = \kappa'(1 - j \tan\delta) \tag{2}$$

where:

$\tan\delta$ = κ''/κ',
κ' = real part, and
κ'' = imaginary part.

The value of κ^* is obtainable from observations that evaluate the attenuation and wavelength of electromagnetic wave propagation in the medium.

6.2 The permittivity of the medium in a transmission line affects the wave propagation in that line. Obtain the dielectric properties of a specimen by using a suitable line as a dielectric specimen holder. The electromagnetic field traveling in one direction in a uniform line varies with time, t, and with distance along the line, χ, as $\exp(j\omega t \pm \gamma\chi)$ where γ is the propagation constant. Assuming that the metal walls of the line have infinite conductivity the propagation constant γ of any uniform line in a certain mode ~~is~~is:

$$\gamma = 2\pi(\lambda_c^{-2} - \kappa^*\lambda^{-2})^{1/2} \tag{3}$$

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[3] The boldface numbers in parentheses refer to the list of references appended to these test methods.

where:

λ_c = cut-off wavelength for the cross section and the mode in question,
$\lambda (= c/f)$ = wavelength of the radiation in free space, and
κ^* = relative complex permittivity of the nonmagnetic medium.

Since κ^* is complex, γ is complex, that ~~is,~~is:

$$\lambda = \alpha + j\beta \tag{4}$$

~~the~~The field dependence on distance is therefore of the form $e^{-\alpha\chi}\, e^{-j\beta\chi}$. The wave attenuation is α in nepers per unit length; β is the phase constant, $\beta = 2\,\pi/\lambda_g$ where λ_g is the guide wavelength in the line. The method of observing α and β by impedance measurements and of representing the behavior of a line containing a dielectric by means of the formalism of transmission line impedance will be outlined briefly (**1**).

6.3 *Impedance Representation of ~~the~~ Ideal Problem*—The impedance representation of the ideal problem is illustrated by Fig. 1 for a uniform line terminated by a short. In Fig. 2 a dielectric specimen of length d_s is supposed to fill completely the cross section of the line and be in intimate contact with the flat terminating short. The impedance of a dielectric filled line terminated by a short (**1**), observed at a distance d_s from the

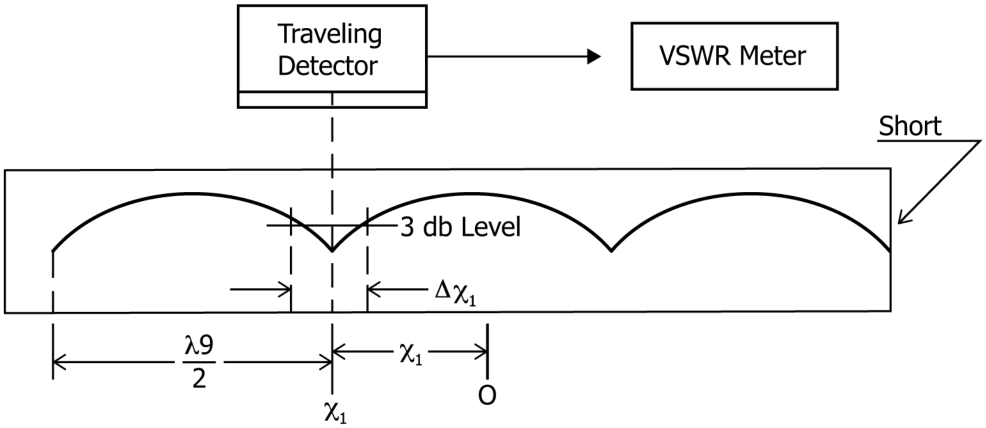


FIG. 1 Standing Wave Established Within Empty Shorted Waveguide

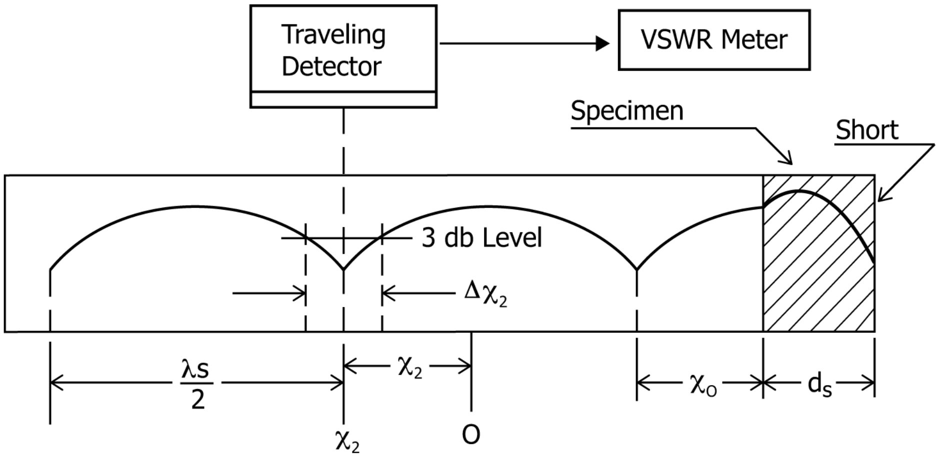


FIG. 2 Standing Wave Established Within Shorted Waveguide After Insertion of Specimen

short (at what is defined as the input face of the specimen) ~~is~~is:

$$Z_{in} = (j\ \omega\ \mu_0/\gamma_2 \tanh\ (\gamma_2 d_s)) \tag{5}$$

where:

μ_0 = the permeability of free space and of the material, and
γ_2 = given by Eq 2, using the dimensions of the line around the specimen.

~~where μ_0 is the permeability of free space and of the material and γ_2 is given by Eq 2, using the dimensions of the line around the specimen.~~

6.4 *Impedance Measurement:*

6.4.1 The object of the measurement is to obtain the impedance at the input face of the specimen for evaluation of the unknown γ_2 in Eq 4 which in turn allows K^* to be evaluated in Eq 2. The impedance in question is measured by a traveling probe in a slotted section of the line. As illustrated schematically in ~~Fig. 1~~Figs. 1 and 2~~ and Fig. 2~~, the position of an electric node, that is, an interference minimum of the standing wave, is observed, and also the "width," $\Delta\chi$, of this node is observed. $\Delta\chi$ is the distance between two probe positions on either side of the node position where the power meter indicates twice the power existing at the node minimum. The voltage standing wave ratio denoted by r (r = VSWR) is obtained from $\Delta\chi$ by the equation (see λ_{gs}, Section 11~~)~~):

$$r = \lambda/\pi\Delta\chi \tag{6}$$

NOTE 3—Refer to ~~Appendix X2~~Appendix X2 and Appendix X3 ~~and Appendix X3~~for additional comments on errors and refinements in the method to improve accuracy. Also refer to Refs **(1-4)** for information on air gap corrections and use of standard materials to reduce errors and improve accuracy.

When r is small, a correction is necessary **(5)**. The load impedance at a phase distance u away from an observed electric node having VSWR = r ~~is~~is:

$$Z_{meas} = Z_{01}(1 - j\ r\ \tan u)/(r - j\ \tan u) \tag{7}$$

where:

Z_{01} = $j\omega\mu_0/\gamma_1 = f\mu_0\lambda_g$, assuming the line is uniform and lossless.

~~where $Z_{01} = j\omega\mu_0/\gamma_1 = f\mu_0\lambda_g$ assuming the line is uniform and lossless.~~

6.4.2 It remains to determine r and u correctly, taking into account losses of the line and nonuniformity due to temperature differences, then to equate Z_{meas} and Z_{in} from Eq 6 and Eq 4, and finally to lay out a convenient calculation scheme for κ^*. The measuring procedure for obtaining r and u is discussed in Section 10.

7. Significance and Use

7.1 This test method is useful for quality control and acceptance tests of dielectric materials intended for application at room and substantially higher temperatures. Dielectric measurement capabilities over wide ranges of temperature and over wide, continuous ranges of frequency provide significant usefulness of this method for research and development work.

8. Apparatus

8.1 See Fig. 3 for a block diagram of equipment components. Some characteristics of the component in each block are as follows:

8.1.1 *Generator*—Stable in power and frequency with low harmonic output.

8.1.2 *Square-Wave Modulator*—1.0 kHz output or frequency required for VSWR meter.

8.1.3 *Frequency Meter*—Heterodyne or cavity absorption; uncertainty 1 part in 10^4.

8.1.4 *Isolator*—30-dB isolation, and having an output VSWR of less than 1.15.

8.1.5 *Slotted Section*—A slotted waveguide section and carriage capable of measuring gross distances to 0.025 mm (0.001 in.) and small distance to 0.0025 mm (10^{-4} in.) (for node width). A micrometer head is required; it is to move parallel to the axis of the line.

8.1.6 *Probe*—Adjustable for depth. The detector must be square law (**6**) if one uses the voltage-decibel scale of the standing wave ratio (SWR) meter. The detector must be operated in the square law region. And, in particular, the crystal detectors will comply with the square law, if they are not overdriven. The law of a crystal is checked commonly by adding a good rotating-vane microwave attenuator.

8.1.7 *VSWR Meter*—Readable in decibels.

8.1.8 *Temperature Isolation Section*—Includes a bend.

8.1.9 *Cooling Sink*—Sufficient conduction to water or air stream to maintain suitable temperature and waveguide dimensions.

8.1.10 *Waveguide Specimen Holder*—Platinum-20 % rhodium for ~~1650°C;~~1650 °C; platinum for temperature ~~1300°C;~~1300 °C; copper or silver for lower temperatures within their abilities to withstand thermal damage and corrosion. Length shall be sufficient to have a main transition region of temperature of the order of λ_g in extent and still keep sample temperature uniform to ~~5°C.~~5 °C.

8.1.11 *Tube Furnace*—Platinum-wound tube furnace to accept test section, and maintain a ~~50-mm~~ 50 mm (2-in.) length at a constant temperature ~~±5°C~~±5 °C up to ~~1650°C.~~1650 °C.

8.2 The so-called slope of the attenuation characteristic of the slotted line is to be normal, that is, the VSWR is changing by the expected amount in going from one node to another while looking into a shorted termination. Items 8.1.5, 8.1.8, and 8.1.10 shall

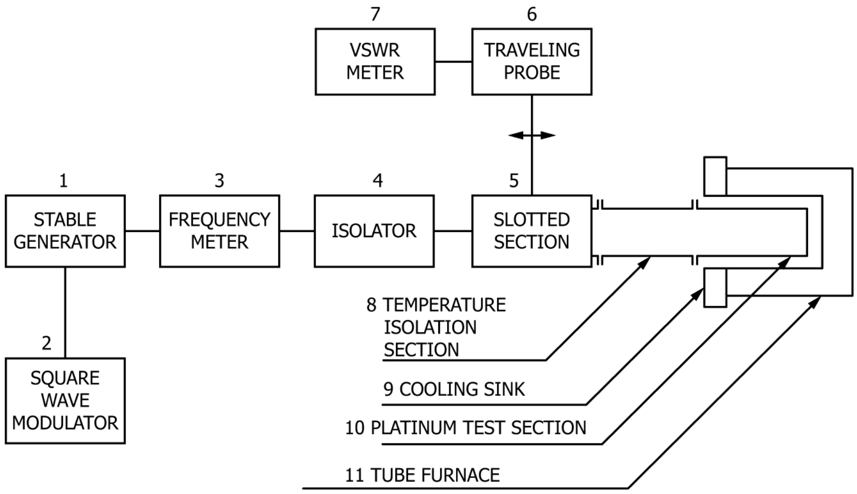


FIG. 3 Block Diagram of Apparatus Used to Perform ~~the~~ Measurement of Dielectric Properties by ~~the~~ Short Circuit Line Method

have initial dimensions plus differential expansions at the temperature of a junction so that the change in dimensions is less than 0.25 mm (0.01 in.). The dielectric holder shall slope downward at 45 to 90° to maintain specimen against termination. Termination shall be flat to 0.010 mm (0.0004 in.) and perpendicular to axis of waveguide within ±0.05°. At 9 GHz, the tolerance on transverse dimensions shall be ±0.075 mm (0.003 in.).

9. Sampling

9.1 Determine the sampling by the applicable material specification.

10. Test Specimen

10.1 The transverse dimensions of the specimen shall be 0.05 ± 0.025 mm (0.002 ± 0.001 in.) less than those of the transmission line. The front and back faces shall be parallel within 0.01 mm (0.0004 in.) and perpendicular to the axis of the transmission line within ~~± 0.05°.~~ ±0.05°. The corners of the specimen are slightly rounded so the end surface seats flat against the termination with no air film between the surfaces. The length, d_s, shall be suitable for the measurement; a length of 1 mm (0.04 in.) shall be used in 1 by ~~23-mm~~ 23 mm (0.04 by 0.9-in.) rectangular waveguide. For high loss materials the length is controlled by the electrical criterion given for $n \tan \delta$ in 12.2.2.

11. Procedure

11.1 Impedance measurements are required in the empty line (Fig. 1), and with the specimen in place (Fig. 2). The frequency of the source and the temperature distribution of the line are to be the same for both observations. With no specimen (Fig. 1) read the position χ_1 of a voltage minimum (a node), on a scale of arbitrary origin; also measure the separation between positions either side of χ_1 where the power is +3.01 dB from the minimum. This is the width $\Delta\chi_1$ of the node. Likewise measure this analogous χ_2 and $\Delta\chi_2$ with the specimen against the termination (Fig. 2). As an additional check measurement, in one case measure the distance between two adjacent nodes. This distance is $\lambda_{gs}/2$, where λ_{gs} is the guide wavelength in the slotted section.

12. Calculation

12.1 *Measurements Transformed to Input Face of Specimen*—When measurements are made at elevated temperatures, the guide width and the guide wavelength, λ_g, vary because of the temperature gradient between the heated section and the cool (room temperature) slotted section. Fortunately the argument of the tangent in Eq 6 is obtainable, assuming the change in λ_g is not abrupt. The correct argument ~~is~~is:

$$u = 2\pi[N/2 - d/\lambda_{gh} \pm (\chi_2 - \chi_1/\lambda_{gs})] \tag{8}$$

~~where~~Where λ_{gh} is calculated for the empty heated dielectric holder section from the dimensions duly adjusted for thermal expansion. In Eq 7 the plus sign is used if the scale for χ increases away from the short, the minus sign if the opposite. N is the smallest integer 0, 1, etc., that makes u positive. To calculate λ_{gh} use the general ~~equation~~equation:

$$\lambda_{gh}^{-2} = \lambda^{-2} - \lambda_c^{-2} \tag{9}$$

where:

λ = c/f = free space wavelength, and
λ_c = cutoff wavelength calculated from the dimensions.

For the TE_{10} mode rectangular guide discussed below, λ_c~~ = 2~~ = 2 a* where a* is the wide dimension. It remains to find the $\Delta\chi$ (width of the node) that would have been measured at the face of the specimen. The node width $\Delta\chi_1$ without the specimen is assumed to arise from the attenuation factor of the empty line, and can be treated as if it increased smoothly with distance from the short. The width contribution accumulated due to attenuation in going from the sample face to the place χ_2 where it is observed is $\Delta\chi_1(L_2 - d_s)/L_1$ where L_i is the total length of path, i = 1 or 2, to the shorting termination and d_s is the length of the specimen. The node width $\Delta\chi$, transformed to the sample face is therefore obtained approximately ~~as~~as:

$$\Delta\chi = \Delta\chi_2 - \Delta\chi_1(L^2 - d_s)/L_1 \tag{10}$$

A more exact treatment would require knowing the attenuation as a function of distance throughout. In a high temperature holder, with $L >> d$, use an adequate ~~approximation~~ approximation:

$$\Delta\chi = \Delta\chi_2 - \Delta\chi_1 \tag{11}$$

12.2 *Equations to Be Solved:*

12.2.1 Setting the impedances from ~~Eq 4~~Eq 4 and 6 ~~and Eq 6~~equal ~~gives~~gives:

$$\frac{\mu_0}{\gamma_2}\tanh \gamma_2 d_s = \frac{\mu_0 \lambda_{gh}(1 - j\ r\ \tan\ u)}{j2\pi(r - j\ \tan\ u)} \tag{12}$$

Dividing by d_s Eq 11 is of the form Z^{-1} tanh Z equal to a known complex number, where $Z = \gamma_2 d_s$. Solutions can be obtained (**1**) and k^* calculated.

12.2.2 If tan δ is less than 0.1 and n tan δ is less than 0.4, where n is the number of half wave segments contained in the specimen, it is a reasonable approximation to separate real and imaginary parts in Eq 11 and obtain (**7**):

$$(\beta_2 d_s)^{-1}\tan \beta_2 d_s = (\lambda_{gh}/2\pi\ d_s)\tan u \tag{13}$$

From Eq 2, assuming tan δ is small,

$$\beta_2 = 2\pi(\kappa\ '\lambda^{-2} - \lambda_c^{-2})^{1/2} \tag{14}$$

which gives κ' after β_2 d_s has been found in Eq 12.

$$\kappa' = [(\beta/2_2/2\pi)^2 + \lambda_c^{-2}]\lambda^{-2} \tag{15}$$

Of course, λ_c is based on the size of the heated waveguide holder. The other part of Eq 11 ~~gives~~gives:

$$\tan\delta = \frac{\Delta\chi}{d_s}FG \tag{16}$$

where:

$$F = 1 - \kappa^2/\kappa'\lambda_c^2 \tag{17}$$

~~and~~and:

$$G = \frac{(1 + \tan^2 u)}{(1 + \tan^2 \beta_2 d) - (\tan\ \beta_2 d/\beta_2 d)} \tag{18}$$

The paper (**7**) on separating Eq 12-17 from Eq 11 is to be consulted. The loss tangent in Eq 15 contains a contribution from the metal walls around the specimen; corrections are available (**2, 7**).

12.2.3 Finally, a correction in κ' (at least, and ideally in tan δ also) is required due to the air gap around the specimen. Theoretical treatment (**3, 8, 9**) indicates that in rectangular TE_{10} ~~guide~~guide:

$$\kappa' = \kappa'_{\mathrm{Eq13}}\frac{b}{b_w - (b_w - b)\kappa'_{\mathrm{Eq13}}} \tag{19}$$

where:

*b*andb_w = the shorter cross-sectional dimensions of the specimen and guide, respectively, taking account of thermal expansion.

~~where b and b_w are the shorter cross-sectional dimensions of the specimen and guide, respectively, taking account of thermal expansion.~~ Some experiments (**10**) disagree with Eq 18. The calculation scheme in Appendix X1 uses experimental corrections.

13. Report

13.1 Report the following information:

13.1.1 The unique identity of the material tested, that is, name, grade, color, manufacturer, or other pertinent data,

13.1.2 Test temperature,

13.1.3 Dimensions of specimen and waveguide holder cross section.

13.1.4 Thermal expansion coefficient of specimen and waveguide at each temperature,

13.1.5 Frequency, *f*,

13.1.6 $\chi_2 - \chi_1$, and

13.1.7 Calculated value of κ' and tan δ.

14. Precision and Bias

14.1 The main sources of error in κ' are from air gaps either between the specimen and the short or in the direction of the electric field. Variations in κ' with the specimen length d_s and due to turning it over frequently indicate a termination air gap. The gap involved in Eq X3.20 is to be carefully evaluated. A weighted average, weighted by the sine squared across the guide, shall be used. Errors in loss arise mainly from imperfection of the probe coupling and from inability to determine the losses q, $\Delta\chi_5$, and $\Delta\chi_t$. It is helpful to verify the measurement system by measuring the loss of a standard reference material having low loss, especially when κ' is of the order of 9 to 10 (see Note 2 in 6.4.1).

TEST METHOD B—RESONANT CAVITY PERTURBATION METHOD

15. Scope

15.1 This test method covers the measurement of microwave complex permittivity of dielectric specimens in the form of rods, bars, strips, sheets, and spheres. The measurement frequency depends on the available resonant modes in a resonant cavity, which limits freedom of selection to a few values of frequency for a given cavity. Resonant cavities exhibit very high *Q* values (2000 to 5000 or more) and are therefore inherently sensitive for low loss measurements. The perturbation method requires that the specimen be relatively small compared to the volume of the cavity and that the specimen must be positioned symmetrically in a region of maximum electric field. Although resonant cavities are sensitive to low loss materials, the small specimen size limits the precision attainable. Nevertheless, the method has several additional advantages besides reasonably good precision:

15.1.1 Although dimensions are important and must be measured accurately, the specimen does not have to have a close tolerance fit within the specimen holder as in Test Method A.

15.1.2 The calculations for the perturbation method are relatively simple, and do not require digital computers or tables of complex functions.

15.2 The specimen shapes mentioned above have been used for ceramics and ferrites as well as homogeneous organic materials. The thin strip or sheet is adaptable to laminates.

~~16. Terminology~~

~~16.1 For definitions of other terms used in these test methods, refer to Terminology D1711.~~

~~16.2 *Definitions of Terms Specific to This Standard:*~~

~~16.2.1 *electrical skin depth, n*—the effective depth of field penetration at high frequencies where electric currents are confined to a thin layer at the surface of conductors due to basic electromagnetic phenomena.~~

~~16.2.1.1 *Discussion*—~~

~~The skin depth for copper and silver is approximately 0.002 mm at 1 GHz and decreases by a factor of 10 at 100 GHz.~~

~~16.2.2 *high Q cavity, n*—a rectangular cavity having a *Q* greater than 2000.~~

~~16.2.2.1 *Discussion*—~~

~~*Q* defines the bandwidth (or sharpness) of the resonance curve of field intensity plotted against frequency. *Q* is the reciprocal of the electrical loss with a high *Q* indicating low electrical losses of the cavity and dielectrics and is obtained by optimum choice of cavity dimensions, use of high conductivity metals (such as silver and copper) with highly polished surfaces (that is, surface roughness much smaller than electrical skin depth at the test frequency). High *Q* is enhanced by choice of large cavity volume to surface area. Surface irregularities or variations in flatness, radius of curvature, or parallelism of walls, leads to spurious resonance modes which introduce electrical losses and lower the cavity *Q*.~~

~~16.2.3 *microwave, adj*—referring to electromagnetic wavelengths of 30 cm or less where the corresponding frequency is 1 GHz or higher.~~

~~16.2.4 *resonant cavity, n*—an enclosure with conducting walls which will support electromagnetic resonance of various specific modes dependent on the cavity geometry and dimensions, and on the integral number of half waves and their directions of propagation as terminated by the cavity walls.~~

~~16.2.4.1 *Discussion*—~~

~~In practice, allowance must be made for input and output coupling holes, probes, or loops. Openings or means of disassembling must be provided for introducing dielectric specimens.~~

16. Summary of Test Method

16.1 The introduction of a dielectric specimen into a resonant cavity lowers the resonant frequency and lowers the *Q* of the cavity. The permittivity and dissipation factor of the specimen can be calculated from measurements of resonant frequency and *Q* of the cavity with and without the specimen, and from cavity and specimen dimensions. When the specimen is small compared to wavelength, perturbation theory allows simplification of the calculations.

17. Significance and Use

17.1 This test method is useful for specification acceptance, service evaluation, manufacturing control, and research and development of ceramics, glasses, and organic dielectric materials. It has also been widely used for magnetic ferrites as Test Method A893/A893M.

18. Interferences

18.1 Test Method A is sensitive to magnetic permeability as well as dielectric permittivity. ~~The~~This test method requires that the relative complex permeability be of unit magnitude. Test Method B is insensitive to permeability since the specimen is small and is introduced in a region where the electric field is maximum and the magnetic field is zero. Although most dielectric materials have relative permeability of unity, there are materials like ferrites where both relative permittivity and permeability are greater than unity.

19. Apparatus

19.1 Fig. 4 is a sketch of a typical rectangular test cavity, which is in reality, a short section of rectangular waveguide. Metallic plates bolted or soldered to the end flanges convert the transmission line into a resonant box. An iris hole in each end plate feeds energy into and out of the cavity. The cavity electrical losses are to be low, which requires the "*Q*" to be greater than 2000 (see 15.1). A clearance hole centered in opposite walls is provided so that cylindrical rod or spherical specimens can be introduced into a region of maximum electric field. Strip or sheet specimens have to be introduced by removing one of the end walls. A list of apparatus follows:

19.2 *Microwave Frequency Meter,* 6-digit precision.

19.3 *VSWR Meters,* or equivalent power indicators, 0.1 dB or less sensitivity.

19.4 *Crystal Diodes and Holders,* or bolometers.

19.5 *Directional Couplers,* or waveguide to coax adaptors.

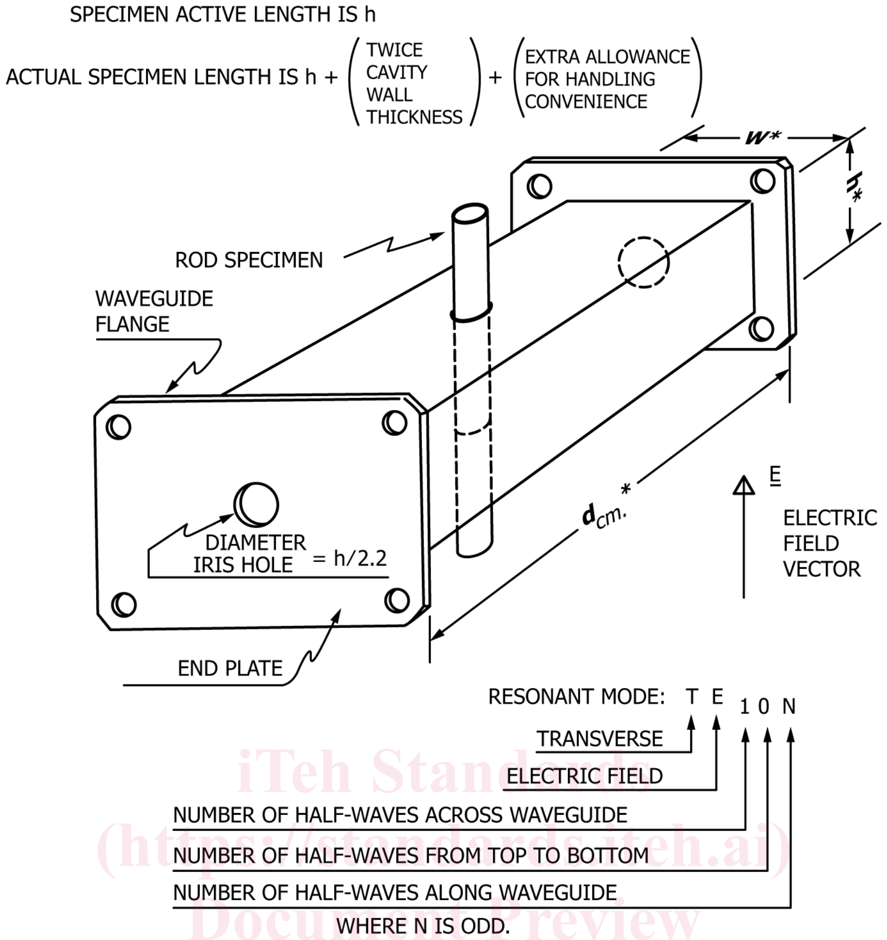
NOTE 4—These items cover one band of frequencies only, such as X band (8 to 11 GHz).

19.6 *Microwave Signal Generator,* adjustable frequency.

19.7 *Square-Wave Modulator* (if VSWR meters used).

19.8 *Variable Attenuator,* precision-calibrated, 0.1 dB or less uncertainty, range 10 dB or more.

~~These items cover one band of frequencies only, such as X band (8 to 11 GHz).~~



Resonant Frequency: $f_0 = 15\ [(1/W)^2 + (N/d)^2]^{½}$ gigahertz.

* *h, w,* and *d* are cavity inside dimensions in centimetres.

FIG. 4 Rectangular Microwave Cavity for Permittivity Measurements by ~~the~~ Perturbation Method

19.9 *Variable Attenuator.*

19.10 *Isolators.*

19.11 *Set Waveguide Hardware,* coaxial cables, connectors, etc.

19.12 Conventional VSWR meters contain high gain amplifiers tuned to 1000 Hz. This requires 1000 Hz modulation. Digital frequency meters generally do not work on square wave modulated signals. A100-MHz digital frequency counter plus a transfer oscillator are often used by mixing a harmonic of the oscillator with the microwave signal to get a "beat frequency" null on an oscilloscope. The counter reads fundamental oscillator frequency, which when multiplied by the number of the harmonic, is equal to the microwave frequency. This method works on either modulated or unmodulated signals.

19.13 A variation of the above system uses an unmodulated signal generator connected to a digital frequency meter, followed by a crystal diode modulator or equivalent. This allows the use of sensitive VSWR meters. If modulation is omitted entirely, microwave power meters can be used, but due to lower sensitivity, a microwave amplifier is necessary to raise the power input above noise level.

19.14 Another approach substitutes a microwave received heterodyne system instead of square wave modulation and VSWR meters. This requires an additional tuned microwave oscillator, which beats against the signal generator to produce a difference frequency of around 30 MHz, which is then amplified by a tuned I.F. amplifier and detector to get a suitable indication on a d-c milliammeter.