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IPC-TM-650
TEST METHODS MANUAL

Number	
2.5.5.5.1	
Subject	
Stripline Test for Complex Relative Permittivity of Circuit Board Materials to 14 GHz	
Date	Revision
3/98	
Originating Task Group	
High Speed/High Frequency Test Methods Subcommittee (D-24)	

1.0 Scope

1.1 Summary This method is for measurement of relative permittivity (ε_r) and dissipation factor or loss tangent (tan δ) of circuit board substrates under stripline conditions. Measurements are made by measuring resonances of a length of stripline over a wide frequency range from below 1 GHz to about 14 GHz[1,2]. The method permits a wide variety of specimen configurations, varying in dielectric thickness, width of center conductor, and use of clad or laid up conductor foil[3]. Sensitivity to differences in tan δ are enhanced by the ability to adjust the degree of coupling to the resonator by adjusting an air gap between probes and the resonator ends. Many of the principles used in IPC-TM-650, Method 2.5.5.5, are applied in this method.

1.2 Terminology Terms used in this method include:

Complex Relative Permittivity—The values for relative permittivity and dissipation factor considered as a complex number.

Permittivity—Dielectric constant (see IPC-T-50) or relative permittivity. The symbol used in this document is ε_r. K' or κ' are also sometimes used.

Relative Permittivity—A dimensionless ratio of absolute permittivity of a dielectric to the absolute permittivity of a vacuum.

Loss Tangent—Dissipation factor (see IPC-T-50), dielectric loss tangent (see 9.2). The symbol used in this document is tan δ.

1.3 Limitations The limitations in described in 1.3.1 through 1.3.4 should be noted.

1.3.1 The measured effective permittivity for the resonator element can differ from that observed in an application.

Where the application is in stripline and the line width to ground plane spacing is less than that of the resonator element in the test, the application will exhibit a greater component of the electric field in the X, Y plane. Heterogeneous dielectric composites are anisotropic to some degree, resulting in a higher observed ε_r for narrower lines.

Microstrip lines in an application may also differ from the test in the fraction of substrate electric field component in the X, Y plane.

Bonded stripline assemblies have air excluded between boards and thus tend to show greater ε_r values than would be obtained with this method using specimen types A or, to lesser extent, B, as discussed in 3.0.

1.3.2 As with IPC-TM-650, Method 2.5.5.5, with specimen type A, or, to a lesser extent, with B (see 3.0), we expect the method to show a downward bias in measured ε_r. This is caused by the electric field crossing clamped dielectric-conductor interfaces with air included in the surface roughness.

1.3.3 With specimen type B, C, or D, the method shows an upward bias in measured tan δ. This is caused by the surface roughness and/or surface treatment of the clad copper foil required for adequate adhesion to the dielectric.

1.3.4 Compared to IPC-TM-650, Method 2.5.5.5, both done with computer automated data collection, this method requires a greater degree of operator skill and more time to prepare specimens and perform measurements.

1.4 Advantages

1.4.1 The sensitivity of the method to differences in ε_r of specimens should be superior to that of IPC-TM-650, Method 2.5.5.5 since the specimen comprises all of the dielectric affecting the measurement.

1.4.2 The method is known to be more sensitive to differences in tan δ than IPC-TM-650, Method 2.5.5.5. We believe the ability to adjust the degree of probe-to-resonator coupling to a low enough value that Q_{loaded} is close to $Q_{unloaded}$ (see 7.2.2) makes this possible.

1.4.3 The method is expected to lend itself to use of stable referee specimens of known electric properties traceable to NIST (National Institute of Standards and Technology).

2.0 Applicable Documents

IPC-MF-150 Metal Foil for Printed Wiring Applications

IPC-TM-650 Method 2.5.5.5, Stripline Test for Permittivity and Loss Tangent (Dielectric Constant and Dissipation Factor) at X-Band

3.0 Test Specimen Specimen length corresponds to an available fixture length L. Longer L values enable lower minimum resonant frequencies to be achieved. L is also the length dimension of the copper plates described in 5.0. Four types of specimens can be used for this method, as shown in Figure 1.

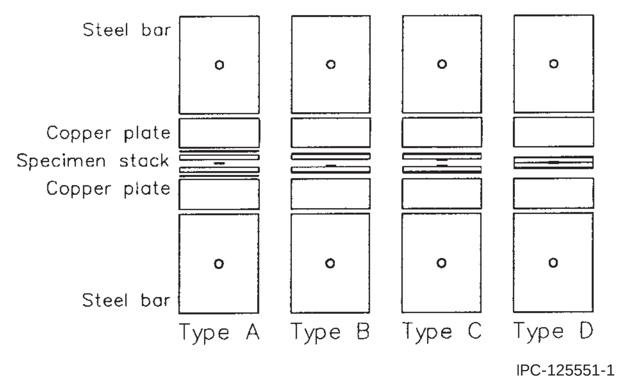

Figure 1 Exploded End Views of Stacked Specimen Types A, B, C and D (See 3.0) with Copper Foil Thickness Exaggerated and Including the Copper Plates (See 5.1.2) and Steel Bars (See 5.1.1) of the Fixture

3.1 Type A Two 25.4 mm wide by L long cards etched free of copper cladding. These are placed on either side of a center strip of smooth copper foil of specified thickness and width and will be assembled between 25.4 mm wide by L long copper foil cards.

3.2 Type B One 25.4 mm wide by L long card with clad copper on one side and copper etched off the other side, and a second card of matching size with clad copper on one side and copper etched off the other side except for a centered strip of specified width extending to both ends of the card. The copper free surface of the first card is assembled against the etched strip of the other to form the stripline resonator.

3.3 Type C Two 25.4 mm wide by L long cards with clad copper on one side and copper etched off the other side except for a centered strip of specified width extending to both ends of the card. The etched strip surfaces of both cards face together to form the stripline resonator.

3.4 Type D Oversize cards similar to type B are bonded together with a selected bonding film and then trimmed to size to form the stripline resonator assembly. This could be a test coupon cut from a bonded stripline circuit board assembly.

For types B, C, and D, the specimen card should first be prepared with about 5 mm or more excess length. Wide pressure sensitive adhesive (PSA) tape can be used to mask the ground plane side, and a narrow PSA tape can be used to mask for the centered strip before etching off exposed copper. Trimming the excess length after etching removes any undercut areas at the ends. Trimming to length should be done in a way that leaves the end surfaces with sharp edges and no conductor edge distortion or smears over that surface. Sanding specimens clamped between paper-phenolic laminate drill-entry boards is an advised method for finishing the end surfaces.

Type A specimens with untreated smooth copper foil will provide the most accurate values for tan δ, but will tend to have a low bias on ε_r. Type C eliminates all clamped interfaces with the air layer between the dielectric and the conductor to give the most accurate ε_r value but, with the copper surfaces treated for adhesion, tends to have a high bias on dissipation factor. Type D gives a good measure of practical performance in an application.

4.0 Suggested Electronic Apparatus The principal components required for the test setup consist of the test fixture described in 5.0 combined with the components described in 4.1, Figure 2, Type A and Type B, or preferably with the system in 4.2, Figure 2, Type C.

4.1 A Test Setup for Computer Automation of Data This requires a microwave signal source, an accurate means of measuring the signal frequency, an accurate means for detecting power level, and an accurate method of determining frequency values above and below the resonant frequency at the half-power level for the test fixture loaded with the specimen.

4.1.1 The following components or equivalent, properly interconnected, can be used most effectively with a computer control program for automated testing.

- Sweep Frequency Generator Mainframe HP8350B
- RF Plug-In, 0.01 to 20 GHz HP83592A
- Power Splitter HP11667A
- Automatic Frequency Counter HP5343A
- Source Synchronizer HP5344A
  Obtained as an interconnected assembly with the counter.
- Coaxial cables and adapters

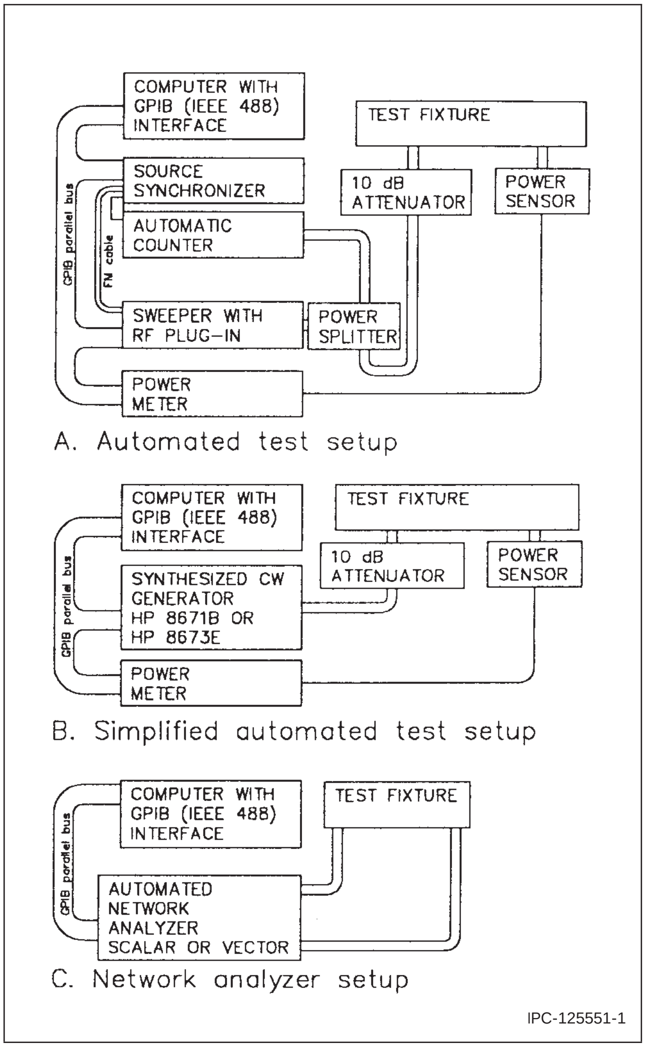

Figure 2 Schematic Drawings of Instrumentation Setups Suitable for Measurements of Permittivity

- 10 dB Attenuator HP8491B
- Programmable Power Meter HP436A
- Power Sensor HP8484A with 70 to 10 dBm range
- IEEE 488 (GPIB) cables
- Controlling computer with GPIB interface

The above equipment is connected as explained in 4.1.1.1 through 4.1.1.3, and as illustrated in Figure 2, Type A.

4.1.1.1 RF Connections The power splitter connects directly to the RF plug-in output. One output of the splitter connects by RF cable to the counter input. The other output is connected by RF cable to the attenuator which connects to one of the test fixture probe lines.

4.1.1.2 Control Connections Connections between counter and synchronizer are provided as specified by the manufacturer. The FM output from the synchronizer connects by BNC to the FM input on the sweeper. GPIB cables connect in parallel to the sweeper, synchronizer, power meter, and computer interface.

4.1.1.3 Other Connections The power sensor is connected to the other probe of the fixture, and its special cable connects into the power meter.

4.1.2 The microwave signal source must be capable of providing an accurate signal. During the required time period and range of frequency needed to make a permittivity and loss tangent measurement, the source must provide a leveled power output that falls within a 0.1 dB range. When the source is set for a particular frequency, the output must be capable of remaining within 5 MHz of the set value for the time required to make a measurement.

The means for measuring frequency shall have a resolution of 0.05% or less and an accuracy of 0.08% or less. An error of +8 MHz in measurement of a resonant frequency near 10 GHz for a material with nominal permittivity of 2.50 represents a -0.004 error in permittivity.

The means for detecting the power level shall have a resolution of 0.1 dB or less and be capable of comparing power levels within a 3 dB range with an accuracy of 0.1 dB. An error of 0.1 dB in estimating half power frequency points can result in an error in the loss tangent of about 0.0001 for a material with 2.5 permittivity. See equation 5 in 7.2.

4.1.3 A synthesized CW generator can be used to replace the sweeper, plug-in, power splitter, connector, and source synchronizer for the simpler set-up shown in Figure 2, Type B.

4.2 Automated Network Analyzer for the Test Setup The instrumentation described in 4.1 may be replaced with either a scalar or vector network analyzer, with test cables connected to the test fixture of 5.0 as the device under test (DUT), as shown in Figure 2, Type A. Examples of automated network analyzers known to be suitable include the Hewlett-Packard 8510 vector network analyzer or the Wiltron Model 561 scalar network analyzer. These or equivalent may be used.

Such instruments may be operated either manually or under computer control with suitable programming to locate the resonant frequency and the frequencies above and below resonance where transmitted power is 3 dB below that at resonance. Network analyzers have several advantages over the instrumentation described in 4.1. Data collection is rapid and may be continuously refreshed with averaging. The log magnitude response curve for ratio of transmitted to incident power (the S21 parameter) as dB versus frequency is visible on a screen for easy verification of a valid resonance. A large number of dB, frequency data points near the resonance, are readily available for optional use of non-linear regression analysis techniques to determine the frequency and Q values with statistically better degrees of uncertainty than those attainable by the three point (f_r, f_1, and f_2) method in either section 6.2 or 6.3.

5.0 Test Fixture

5.1 Fixture Parts for Clamping L is the selected length for the specimen. A fixture may include hardware for more than one value of L. Suggested L values are 50.8, 76.2, 152.4, and 304.8 mm. Since the fundamental resonant frequency and its harmonics are inversely proportional to the value of L for a given ε_r, the selection of an L value determines the low frequency at which the material may be measured for ε_r and tan δ. Figure 1 shows the end views of a series of specimen configurations and includes the parts for clamping.

5.1.1 For each L value, two ground tool steel clamping bars 25.4 mm x 28.58 mm x (L-6.35), as shown in Figure 3. These are intended to provide uniformly distributed force along the length of the specimen, transferred through part 5.1.2. A recommended practice is to provide these with a small diameter threaded rod, such as #4-40, centered on each end and extending about 20 mm to serve as a means for attaching the probe assembly of 5.2 used in 6.1.5 or the alignment jig of 5.1.3 used in 6.1.1.

5.1.2 For each L value, two pure copper ground plates 25.4 mm x 9.52 mm x L with all edges sharp as in Figure 4. These provide at the ends a copper surface perpendicular to the specimen length direction, which serves as a contact area over a range of specimen thicknesses for making ground continuity to the coaxial probe. When these are clamped with 5.1.1 as described in 6.1.1, the inside corners at each end between the outer face of 5.1.2 and the end surface of 5.1.1 form reference locations equidistant from the center line of the stripline resonator element that are used by the probe assembly 5.2 to align the coaxial probe with that center line.

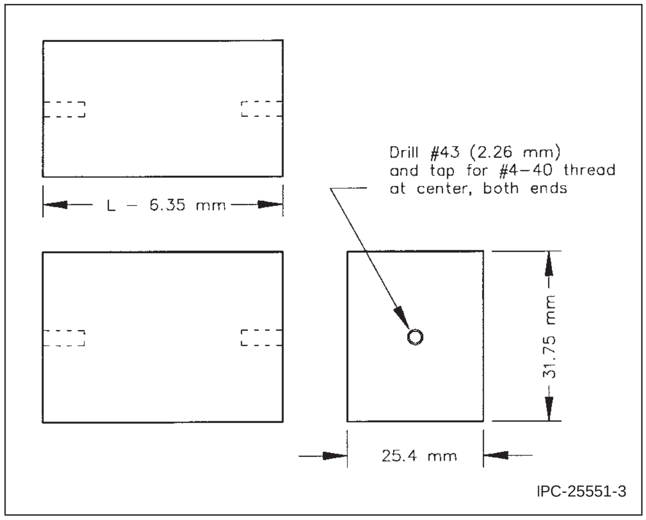

Figure 3 Three View Drawing of a Steel Clamping Bar (See 5.1.1) Cut to Length for the 50.8 mm L Value (Extended #4-40 Threaded Rod Both Ends is Not Shown)

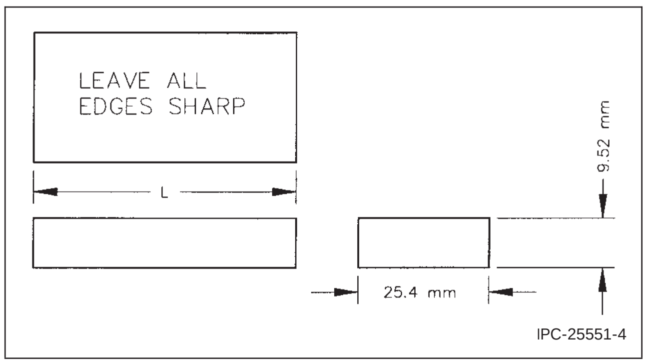

Figure 4 Three View Drawing of a Copper Ground Plate (See 5.1.2) for the 50.8 mm L Value

5.1.3 A stacking alignment jig as used in 6.1.1 of an appropriate design. Figure 5 shows a suggested design.

5.1.4 A low profile mechanical force gage with 4.45 kN compression capacity such as a Dillon Model U, PN 30482-0053, available from Dillon Quality Plus, Inc., 1140-T Avenida Acaso, Camarillo, CA 993012. One is needed for each of part 5.1.5.

5.1.5 A clamping arrangement with 5.1.4 properly mounted in the line of force and with alignment parts for assuring the line of force is properly located through the stack assembled

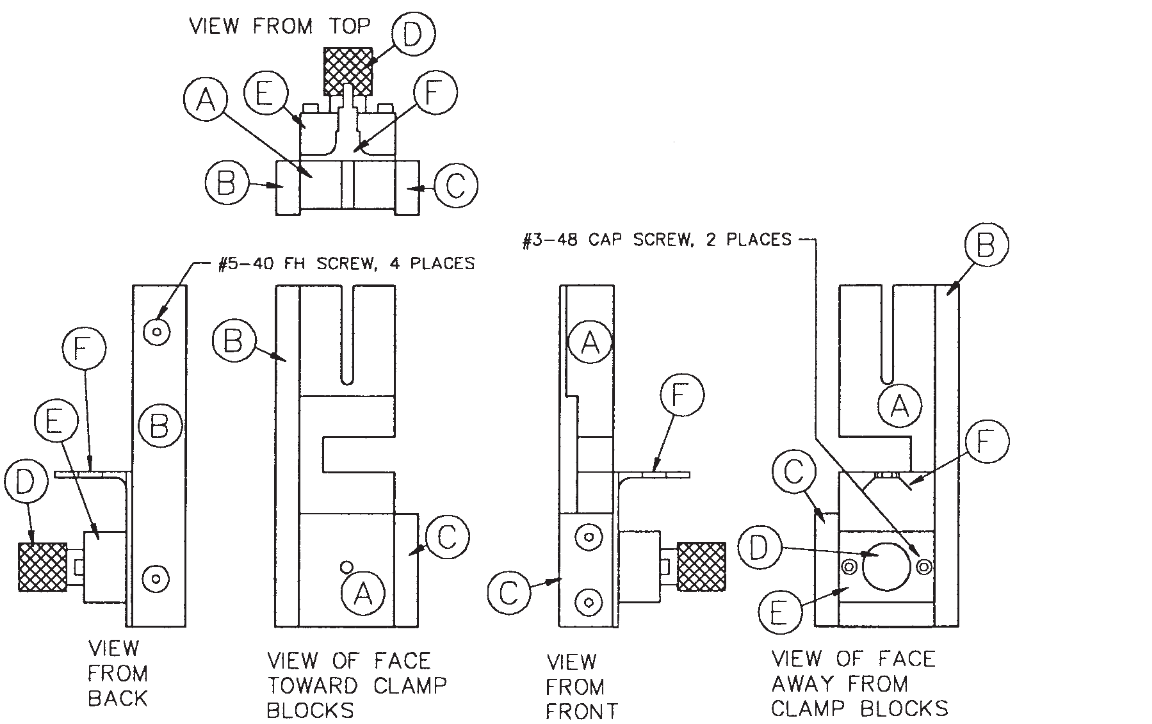

Figure 5 Five Assembly Views for a Suggested Two Member Stacking Alignment Jig (See 5.1.3)
Note: Only the right-handed member is shown. Part A with 3.175 mm deep recessed area on the face towards the clamp blocks assures 6.1.1 items b, c, and d. Its notched out area allows 6.1.1 item 5. Part B assures 6.1.1, item a. Part C eases mounting the jig member to the end of the lower steel bar (see 5.1.1). Knurled #4-40 nut D, retained by E, fastens A against the steel bar with its extended threaded rod. Part F assists in meeting 6.1.1, item e.

according to 6.1.2. This can be a manually adjustable mechanical screw fixture such as a vise, clamp, or a pneumatic cylinder fixture with a pressure regulator. One of component 5.1.5 with 5.1.4 is needed for every 152 mm of specimen length L. See Figure 6.

5.2 Probe Assembly Two probe assemblies are needed; one for each end of the clamped stack. They can be designed to be attached to the ends of the clamp bars 5.1.1. The following items are needed for each assembly.

5.2.1 Semi rigid coaxial cable 1.8 mm size about 230 mm long with 3 mm connector and adapters to the electronic instrumentation. The probe end of the cable has the center conductor extending 1.8 mm.

5.2.2 Copper fitting with reversed bevel soldered to the end of the coaxial cable jacket, as shown in Figure 7.

5.2.3 A means for effecting ground contact between 5.2.2 and both of 5.1.2. Figure 8 shows a suggested beryllium-copper alloy wire part. Two are required, as shown in the sectional views of Figure 9.

5.2.4 Mechanical assembly capable of attaching to the ends of 5.1.1 and using the locations of the inside corners of 5.1.1 and 5.1.2 to align parts 5.2.1 through 5.2.3 with the center line of the stripline resonator. It must accommodate various specimen thicknesses, provide alignment of 5.2.1 through 5.2.3, make contact pressure of 5.2.3 to 5.1.2, provide controlled adjustment of the gap between specimen end and 5.2.1, and provide support for the coaxial cable connector to the instrumentation.

A wide variety of hardware designs for accomplishing the alignment required in 6.1.5 are acceptable if the following conditions are met for each of the two probes:

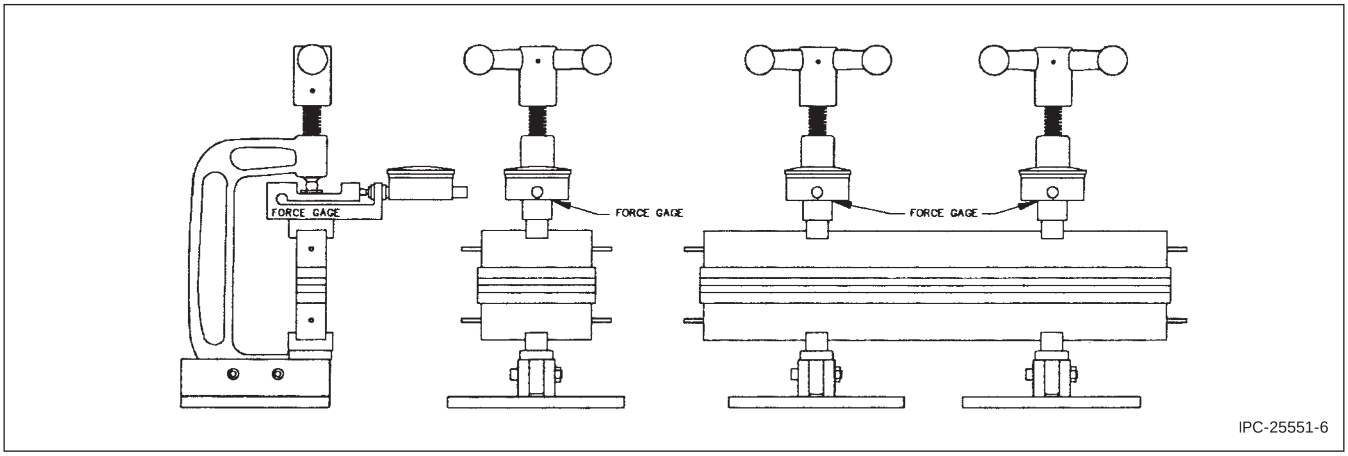

Figure 6 Clamp Arrangement (See 5.1.5) Showing Side and Front Views for Specimen Lengths of 76.2 mm and 304.8 mm

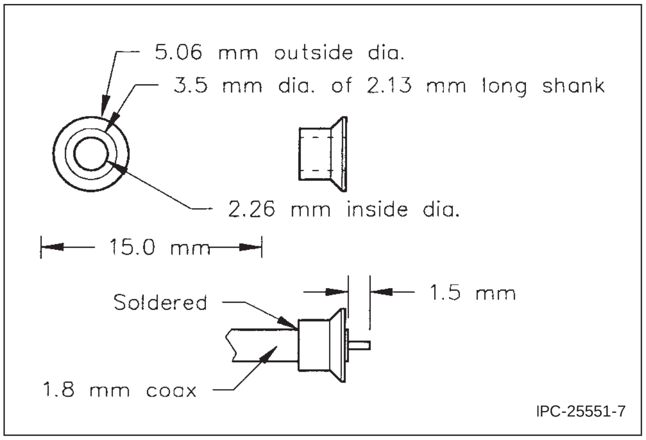

Figure 7 Copper Fitting with Reverse Bevel (See 5.2.2) Soldered to the 1.8 mm Semi-Rigid Coaxial Cable Probe

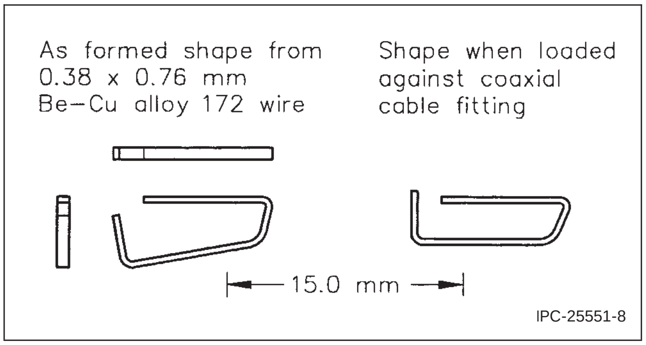

Figure 8 Formed Be-Cu Alloy Wire for Ground Continuity from Coaxial Cable Fitting to Copper Ground Plate

- The center line of the coaxial cable end and the centerline of the stripline resonator in the specimen are aligned within a tolerance of 0.2 mm vertically and horizontally.
- Both parts 5.2.3 (Figure 8) are held aligned so they are centered in a vertical plane through the probe axis, each making firm electrical contact to 5.2.2 (Figure 7) and to the end edge surface of part 5.1.2 (Figure 4).
- The coaxial probe end longitudinal position is adjustable so that the gap between it and the specimen center conductor is controllable to a tolerance of ± 0.03 mm.

6.0 Measuring Procedure

6.1 Preparation for Testing The actual length of the specimen and resonator element shall be determined by a vernier caliper or other means capable of accuracy to ± 0.03 mm or smaller.

Unless otherwise specified, specimens shall be stored before testing at 18°C to 24°C and 50% ± 5% relative humidity. The referee minimum storage time is 16 hours. Shorter times may be used if they can be shown to yield equivalent test results.

If electronic equipment as listed in 4.1 is used, it shall be turned on at least one half hour before use to allow warm-up and stabilization. The automatic frequency counter listed in 4.1 is provided with temperature control of the clock crystal that operates even when the power switch is off. Care should be taken to assure that power is continuously supplied to this unit to avoid a longer warm-up time. Other equipment using vacuum tube devices will require a longer warm-up time, as specified in the manufacturer's literature.

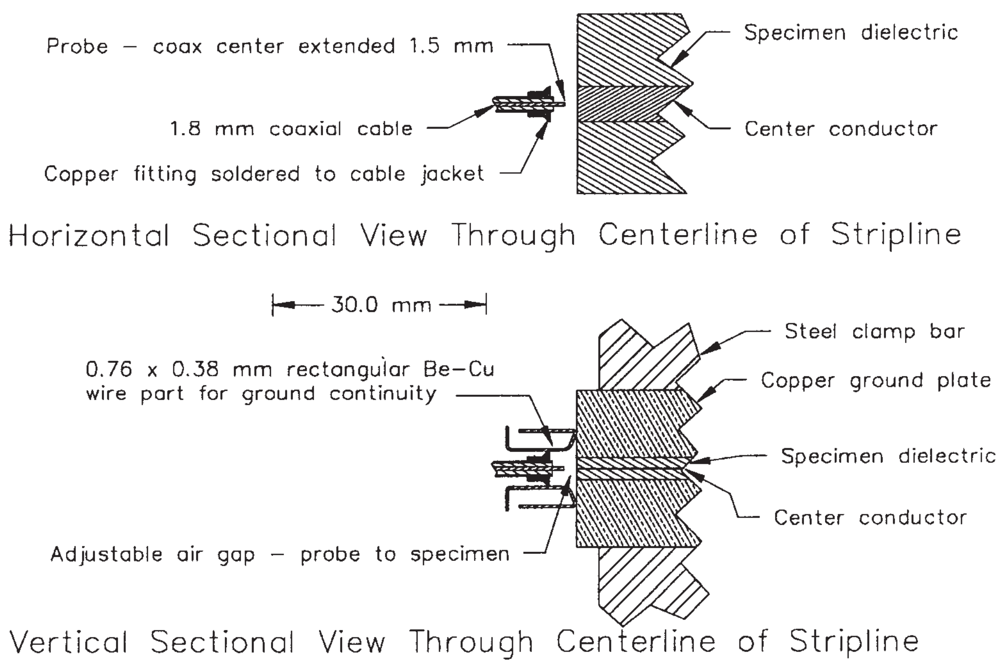

Figure 9 Probe Assembly Position (See 6.1.5) for One End of the Clamped Stack
Note: This figure shows coaxial probe with fitting and Be-Cu alloy wire for ground continuity without showing supporting mechanical structures and adjustments.

This method is best suited for measurements at ambient temperatures in a controlled laboratory atmosphere. It may be possible to adapt it for measurements at other temperatures.

6.1.1 The steel clamping bars, copper clamping plates, and the specimen assembly with copper foil are stacked with the help of a jig (Figure 5) to assure the following:

a) One side surface or edge of each steel bar, copper plate, specimen card, and ground plane copper foil lie in a common plane.

b) The end surfaces of the steel bars lie in a common plane within a 0.1 mm tolerance.

c) The ends of the copper plates extend beyond the steel bars equally on both ends within a 0.1 mm tolerance.

d) The ends of copper plates, specimen cards, and copper foil ground planes lie in a vertical plane within a 0.1 mm tolerance.

e) In the case of specimen type A, the center conductor, whose length extends enough beyond both ends of the specimen cards to be gripped in tension and positioned, is centered across the width of the specimen cards.

6.1.2 The stack formed in 6.1.1 is clamped with a specified total force. For a selected specimen length of 153 mm or less, the force is applied through a force gage in a line centered on the outer faces of the steel bars. For greater lengths, the force should be distributed through force gages at two or more positions not further than 153 mm apart along the length to get uniformity of force per unit length along the specimen length with minimal deflection of the steel bars. Thus, for a 304.8 mm length, apply equal forces at the 76.2 mm and 228.6 mm positions. If a 381 mm was used, apply force at the 63.5 mm, 190.5 mm, and 317.5 mm positions.

6.1.3 Remove the alignment jig used in 6.1.1.

6.1.4 For type A specimens, the center copper strip will still be extending beyond the plane formed by the surfaces of the copper plates, ground foil, and specimen end. This is clipped off cleanly flush with that plane. One preferred method for doing this is to use a lever-action toe nail clipper with a convex shaped cutting pattern modified by grinding so that the metal extending beyond the cutting edges is removed so that the cutting edges are able to reach to the specimen edge for cutting the copper strip.

An alternate method for trimming the copper strip is to use a sharp scalpel. However, this can smear the copper across that the specimen end surface, especially with thin specimens, and may introduce end fringing errors on short L values.

6.1.5 Fasten the probe assemblies to the clamped stack at both ends so that the coaxial cable probe end is centered on the stripline resonator center line. Adjust the assembly so the contact areas on the soldered copper fitting make firm electrical contact by the wires to both top and bottom copper plates. Figure 9 shows by vertical and horizontal sectional views through the stripline resonator centerline this relationship among:

- the copper ground plates (see 5.1.2).
- the specimen with conductors (see 3.0).
- the coaxial cable with extended center conductor end (see 5.2.1).
- the copper fitting (see 5.2.2) soldered to the coaxial cable.
- the wire connection (see 5.2.3).

For the purpose of this method horizontal orientation is parallel to the plane of the specimen surface in the fixture. See three requirements under 5.2.4.

6.1.6 Adjust the position of the coaxial cable probe ends so the air gaps they form with the stripline resonator element are equal. This may be done with the help of a network analyzer set for lowest frequency by adjusting the gaps smaller until each causes a sudden shift in reflected or transmitted power, then adjusting them back to a small gap value, equal on both ends.

6.1.7 With the probe's longitudinal position set to a small air gap such as 0.05 mm, use an appropriate means with the electronic instrumentation to identify the approximate location of the lowest resonant frequency (the fundamental where the resonator length is half the wavelength in the material being tested) and a series of resonances (harmonics) up to the highest frequency of interest. Ideally harmonic resonances occur at each integer multiple of the fundamental resonance. The integer multiples are the values of n in formula 1 of section 7.1. Select which of these resonances will be measured as discussed in section 6.3, 6.4, or 6.5.

6.2 Adjustment of Air Gap for Each Resonance Before the measurement at each resonance, adjust the air gaps at each probe an equal amount to get the dB insertion loss at the maximum transmission to a recommended value between 49.5 and 51.5 dB. As resonant frequency is increased from resonance to resonance for a given specimen, the gap required for a nominal 50 dB insertion loss at resonance tends to increase. A high value dB minimizes the correction for unloaded Q and makes this correction less sensitive to poor data on the baseline dB of the instrumentation. Too high a dB value will put the measurements down in the noise region of the instrumentation, making results less certain and less reproducible.

6.3 Manual Measurement of the Specimen The following procedure is most applicable where only equipment as described in 4.1 is available. The equipment of 4.2 could also be operated manually.

6.3.1 The resonant frequency shall be found by scanning frequency over the expected transmission range of the test resonator. The frequency shall be precisely adjusted to get a maximum reading of power in dB.

6.3.2 Determine half power points by adjusting frequency to give three dB readings both above and below the maximum transmission frequency. Measure each frequency with the frequency meter and record the results:

- f1 - 3 dB down, below the maximum transmission frequency.
- f2 - 3 dB down, above the maximum transmission frequency.

6.4 Automated Measurement of the Specimen For an automated system to be used in performing the measurement, computer software is needed that will collect paired values of frequency and transmitted power. From this data, the frequency for maximum power transmission and the frequencies of the half power points are determined. The computer program may optionally include computation of permittivity and loss tangent as described in section 7.0. Results and collected data may be displayed on the screen, stored in a disk file, sent to a printer, or any combination of these.

In one possible mode of operation, with the equipment described in 4.2, the sequence of steps described in 6.4.1 through 6.4.4 is performed as many times as necessary to get enough data to complete the test procedure. The computer is designated as the controller on the GPIB.

6.4.1 The computer sets the sweeper to a selected carrier wave frequency without an AM or FM audio signal and to a desired output power level, such as 10 dBm.

6.4.2 The same frequency is given to the synchronizer with instructions to lock the frequency of the sweeper to the specified value.

6.4.3 The computer checks the synchronizer for status until the status value indicates the frequency is locked.

6.4.4 The power meter reading is obtained by the computer. Since it takes a finite amount of time for the power sensor to stabilize, either a delay is used or the reading may be taken repeatedly until consecutive readings meet a given requirement for stability.

6.5 Use of the Network Analyzer for Measurement of the Specimen An automated network analyzer may be used either by operating the front panel controls manually or under computer control with suitable specialized software. The fixture with the specimen is connected by test cables and adapters as a device under test. Set up the instrument so the Cartesian screen display shows the S21 parameter, the transmission/incident power ratio, in negative dB vertical scale units versus frequency on the horizontal scale. Select the start and stop frequency range to sweep across the resonance peak and at least 3 dB below the peak. Adjust the start and stop frequency values as narrowly as possible, but still include the resonant peak and the portions of the response curve on both sides of it that extend 3 dB downward.

6.5.1 The first option is to get the three points (f_r, f_1 and f_2) as described in 6.3 or 6.4. Determine the resonant dB_r and frequency f_r values for the highest point (maximum) on the response curve. With manual operation, instrument program features may be available to do this very quickly. On the response curve to the left and right of f_r, locate the f_1, dB_1 and f_2, dB_2 points as near as possible to 3 dB below dB_r. These may then be used in the calculations shown in 7.2.

6.5.2 A second option requires a computer external to the instrument. Collect from the network analyzer all of the f, dB data points represented by the response curve between f_1, dB_1 and f_2, dB_2 and apply non-linear regression analysis techniques to determine statistically values for Q_{loaded}, f_r and dB_r that best fit the f_i, dB_i paired data points to the formula.

$$dB_i = dB_r - 10 \log_e(10) \log_e (1 + 4 Q_{loaded}^2 (f_i / f_r - 1)^2) \quad [1]$$

where 10 $\log_e(10)$ is the constant for converting from $\log_e$ to dB. This formula may be derived from formula 5 with the reasonable assumption that $f_r - f_1$ equals $f_2 - f_r$. The statistically derived values for f_r and Q would then be used in formulas 2 of section 7.1, formula 3 of section 7.2, and formula 6 of section 7.3 respectively.

This has been found to fit the collected data points very well at all regions across the entire f_1 to f_2 range. It is a simplified version of the non-linear regression method for complex S21 parameters described by Vanzura[4].

7.0 Calculations

7.1 Stripline Permittivity Use special care to assign the correct n value for each resonance measured.

At resonance, the electrical length of the resonator circuit is an integral number of half wavelengths. The effective stripline permittivity, ε_r, can be calculated from the frequency of maximum transmission as follows:

$$\varepsilon_r = [n\,C / (2 f_r (L + \Delta L))]^2 \quad [2]$$

where n is the number of half wavelengths along the resonant strip of length L in mm, ΔL is the total effective increase in length of the resonant strip due to the fringing field at the ends of the resonant strip, C (the speed of light) is $2.9978 \cdot 10^{11}$ mm/s, and f_r in Hz (or cycles/s) is the measured resonant (maximum transmission) frequency.

The resonator ends coincide with the end edges of both the dielectric and the ground planes. The relative fringing field at the ends becomes extremely small. It has been the practice with this method to ignore this fringing field and consider the ΔL value to be zero in the calculation of stripline permittivity.

7.2 Calculation of Effective Dielectric Loss Tangent

$$\tan \delta = 1/Q_{unloaded} - 1/Q_c \quad [3]$$

where:

$1/Q_c$ is the loss factor of the conductor

$1/Q_{unloaded}$ is the total loss factor of the unloaded resonator due only to the dielectric, copper, and copper-dielectric interface, and does not include loss due to coupling of the probes.

7.2.1 The resonator loss factor The measurement of the resonance gives a value for the loss factor of the resonator with loading due to probe coupling ($1/Q_{loaded}$).

7.2.1.1 For the three point measurement described in 6.5.1, the calculation is

$$1/Q_{loaded} = [(f_2 - f_1) / f_r] \quad [4]$$

A more exact calculation can be used that does not require that the values of f_1 and f_2 be at exactly half the power level of the maximum at resonance. This is especially suited for automated testing. The formula is

$$1/Q_{loaded} = (1 - (f_1 / f_r)) (10^{\Delta 1//10} - 1)^{-0.5} + ((f_2 / f_r) - 1) (10^{\Delta 2/10} - 1)^{-0.5} \quad [5]$$

where:

$\Delta 1$ is the positive dB difference in power level from f_r to f_1, and

$\Delta 2$ is the positive dB difference in power level from f_r to f_2.

7.2.1.2 For the many point measurements of the resonance described in 6.5.2, the non-linear regression to fit the formula 1 derives the Q_{loaded} value.

7.2.2 Correcting the Resonator Loss Factor for Loading The probe gap set for about 50 dB insertion loss at resonance is intended to make Q_{loaded} approximately equivalent to $Q_{unloaded}$. Nevertheless, corrections in the measured total loss value, $1/Q_{loaded}$ are desireable. *With the assumption that the S21 parameter with straight through connection without the test fixture is at 0 dB, dBr,* the insertion loss or S21 parameter in dB units at the resonant peak, is related to the power ratio by

$$P_2/P_1 = 10^{(-dBr /10)}$$

where the dBr value at resonance is taken as positive. Then the correction is

$$Q_{unloaded} = Q_{loaded} / [1 - (P_2/P_1)^{0.5}]$$

or

$$Q_{unloaded} = Q_{loaded} / [1 - 10^{(-dBr /20)}] \quad [6]$$

As can be seen from the following tabulation at high degrees of insertion loss such as 50 dB errors in the *straight through connection assumption above* are not as important as they would be at lower values such as 20 or 15.

dB	60	50	40	30	20	15	10	5
Q_U/Q_L	1.00	1.00	1.01	1.03	1.11	1.22	1.46	2.28

7.3 Calculation of $1/Q_c$ The following calculation scheme is used to estimate the conductor loss[5,6] needed for formula 3:

$$1/Q_c = \alpha_c C/(\pi f_r (\varepsilon_r)^{0.5}) \quad [7]$$

where:

α_c = $4 R_s \varepsilon_r Z_0 Y / (377^2 B)$ = attenuation constant, nepers/mm

R_s = $0.00825 f_r^{0.5}$ = surface resistivity of copper, Ohms

Z_0 = $377/(4 \varepsilon_r^{0.5} (C_f + (W/(B - T))))$
= characteristic impedance of resonator, Ohm

377 = 120π. = free space impedance, Ohm

C_f = $(2 X \log_e(X+1)-(X-1)\log_e(X^2-1))/ \pi$

Y = $X + 2 W X^2 / B + X^2 (1 + T / B) \log_e [(X + 1) / (X - 1)] / \pi$

X = $1 / (1 - T / B)$

ε_r = relative permittivity

B = ground plane spacing, mm

W = resonator width, mm

T = resonator conductor thickness, mm

Proven data is not currently available for correcting this calculated value to account for increased conductor loss associated with roughness of the copper foil or surface treatments for adhesion. When smooth rolled copper foil is used in Type A specimens the estimate seems quite reliable in the 0.4 to 15 GHz range based on work done with neat (PTFE) poly(tetrafluoroethylene) sheet specimens[3].

8.0 Report The report shall contain the following:

8.1 The type of specimen: A, B, C, or D.

8.2 For specimen type A, if not copper foil type W (wrought), grade 5 (as rolled-wrought), bond enhancement N (none, no stain proof), or for specimen types B, C, or D, state at least: metal, type, grade, and bond.

8.3 The measured length of the resonator and specimen dielectric.

8.4 The measured thickness of specimen cards or, if applicable, of stacks.

8.5 The center conductor width.

8.6 The center conductor total thickness (for type C, this is twice the cladding thickness).

8.7 The temperature of the test fixture, if not in the 21°C to 23°C range.

8.8 Any conditioning prior to measurement.

8.9 The orientation of the resonator with respect to X or Y axis of the specimen.

8.10 For each resonance, show 8.10.1 through 8.10.9.

8.10.1 The node number n.

8.10.2 The calculated effective stripline permittivity.

8.10.3 The calculated effective dielectric loss tangent.

8.10.4 The resonant frequency, f_r, at maximum transmission.

8.10.5 The insertion loss at resonance, dB_r, at maximum transmission.

8.10.6 The Q_{loaded}. (optional).

8.10.7 The calculated $Q_{unloaded}$ (optional).

8.10.8 If the three point method of 6.3, 6.4, or 6.5.1 is used, report the frequency and dB value of the two points either side of the peak (optional).

8.10.9 If the non-linear regression (NLR) method of 6.5.2 is used, report the number of data points used, NLR uncertainty values (for f_r, Q_{loaded}, dB_r) and the standard deviation of the fit in dB units (optional).

9.0 *Notes*

9.1 Permittivity The dielectric of a stripline circuit affects the electrical response of all the circuits printed on it. Velocity of propagation, wavelength, and characteristic impedance all vary with permittivity. If the permittivity varies from the design value, the performance of such circuits is degraded.

Throughout this document, the term ‘‘permittivity’’ refers to relative permittivity of the dielectric material, a dimensionless ratio of the absolute permittivity of the material to that of a vacuum.

9.2 Loss Tangent The attenuation and Q (figure of merit) of stripline circuits are a function of combined copper and dielectric loss. An excessively high loss tangent leads to loss in signal strength and to degraded performance of frequency selective circuits such as filters.

9.3 Dielectrics Clad with Thick Metal on One Side This method can be used for measurements of dielectric substrates with thin foil on one side and thick cladding such as aluminum sheet on the other by using the Type C specimen configuration. In some cases, with very thick metal cladding it may be necessary to use a modified part 5.1.2 (Figure 4) with a reduced thickness dimension.

9.4 Anisotropic Materials For anisotropic materials, test methods in which the electric field is not imposed on the dielectric in a stripline configuration can give misleading values of effective stripline permittivity and loss tangent. This test method measures an effective stripline permittivity when the specimen configuration is close to that of the application.

10.0 References

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6. *Problems in Strip Transmission Lines*, Cohn, S. B., IRE Transactions MTT 3 (March 1955): pp. 119-126.