IPC

*ASSOCIATION CONNECTING
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Number
2.5.5.5
Subject
Stripline Test for Permittivity and Loss Tangent (Dielectric Constant and Dissipation Factor) at X-Band

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Originating Task Group
High Speed/High Frequency Test Methods Subcommittee (D-24)

IPC-TM-650
TEST METHODS MANUAL

1.0 Scope

1.1 Summary This method is intended for the rapid measurement of the X-band (8.00 to 12.40 GHz) apparent relative stripline permittivity (see 9.1) and loss tangent of metal clad substrates. Measurements are made under stripline conditions using a resonant element pattern card, which is separated from the ground planes by sheets of the material to be tested. Further information about this method may be found in ASTM D3380-75.

1.2 Definitions 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 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. The symbol used in this document is tan δ (see 9.2).

1.3 Limitations The following limitations in the method should be noted. Users are cautioned against assuming the method yields permittivity and loss tangent values that directly correspond to applications. The value of the method is for assuring consistency of product, thus reproducibility of results in fabricated boards.

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 groundplane 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, thus tend to show greater ε_r values.

1.3.2 High degrees of anisotropy of some composites can result in an increased degree of coupling of the resonant element, resulting in a falsely lower Q value. If a correction is not applied either mathematically as in 7.2.2 or by deviating from the probe gaps specified for the test pattern, an upward bias in the calculated loss tangent will result.

1.3.3 The sensitivity of the method to differences in ε_r of specimens is impaired by the fact that the resonator pattern card remains as part of the fixture and at the same time constitutes a significant part of the dielectric involved in measurements.

1.3.4 The method does not lend itself to use of stable referee specimens of known electric properties traceable to The National Institute of Standards and Technology (NIST).

2.0 Applicable Documents

2.1 IPC

IPC-T-50 Terms and Definitions

IPC-MF-150 Metal foil for Printed Wiring Application

IPC-TM-650 Method 2.3.7.1, Cupric Chloride Etching

IPC-TM-650 Method 2.5.5.3, Permittivity (Dielectric Constant) and Loss Tangent (Dissipation Factor) of Materials (Two Fluid Cell Method)

ASTM D3380-75 Standard Method of Test for Permittivity (Dielectric Constant) and Dissipation Factor of Plastic-Based Microwave Circuit Substrates

3.0 Test Specimen All metal cladding shall be removed from the material to be tested by any standard etching process, including rinsing and drying; however, IPC-TM-650, Method 2.3.7.1, shall be used as a referee procedure. The test specimen shall consist of a set of two sheets (or two packets of sheets) of a preferred size of at least 51 mm x 69 mm.

3.1 A smaller size may be used if it has been shown not to affect results. The minimum vertical dimension must extend

from the base boards to the top of the 25.4 mm x 51 mm area to which clamping pressure is applied. The minimum horizontal dimension must be enough to extend at least 6.5 mm beyond the center line of the vertical portion of the probe line on either side. For the pattern card of Figure 4 and fixture of Figure 12, these minimums are 38.1 mm x 68.6 mm. For the smaller size, the clamp force in 6.1 or Table 1 is not changed because the effective area over which the force is applied is not reduced. The test fixture is designed to accommodate a total specimen thickness of either 3.18 mm ± 0.22 mm or 2.54 mm ± 0.18 mm from an even number of layers.

NOTE: Testing of built-up specimens introduces error, which can exceed 5% due to air gaps. Exact correlation factors and techniques must be agreed upon or other methods of test used. The 1 MHz method of IPC-TM-650, Method 2.5.5.3, can be used with a correction factor based on tests of samples of the nominal thickness of Table 1 using both techniques.

With some material types not based on woven fabric reinforcement, it is possible to machine specimens to achieve the nominal thickness for test.

4.0 Suggested Electronic Apparatus The principal components required for the test setup consist of the test fixture described in 5.0, 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.

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 5 MHz or less and an accuracy of 8 MHz or less. An error of +8 MHz in measurement of a resonant frequency 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 7.2, equation 5.

4.1 Manual Test Setup The method of determining the half-power points depends partly on the type of signal source used. If the power input to the test fixture is maintained constant as the frequency is varied, then an SWR meter may be used to determine the half-power points at the output of the test fixture. This may be accomplished by using a leveled sweep generator or by using a tunable klystron (at a considerable savings) and manually adjusting the power input to the test fixture to a prescribed level by use of a variable attenuator. A typical equipment list is shown below. Equivalent makes and models of equipment may be substituted where it can be shown that equivalent results are obtained. For example, if a leveling system is not used and the power output of the source varies widely with frequency, a ratiometer may be substituted for the two SWR meters. If only permittivity is desired, it is not necessary to level the input.

The following equipment, or equivalent, may be used.

- Sweep Frequency Generator H.P. 8350B or 8620C
- X-Band Frequency Plug in Unit H.P. 83545A or 86251A
- Frequency Meter H.P. X532B
- Crystal Detector (2) H.P. 423B (Neg)
- Matched Load Resistor for one Crystal Detector H.P. 11523A, opt. 001
- SWR Meter (2) H.P. 415E
- Directional Coupler HP 779D
- 10 dB Attenuator H.P. 8491B
- 8.9 kN Dillon Force Gauge, Compression Model X, Part Number 381612301, with ± 1% full scale accuracy
- Vise or press that is able to exert controlled 4.45 kN force on the test fixture and that opens at least 127 mm to accept the force gauge and test fixture
- Semi-rigid Coaxial Cable and Connectors
- Waveguide to Coaxial Adapters (2) H.P. X281A
- The measuring equipment shall be connected as shown on Figure 1.

4.2 A Test Setup for Computer Automation of Data The following components or equivalent, properly interconnected, can be used most effectively with a computer control program for automated testing.

- Sweep Frequency Generator Mainframe H.P. 8350B

- RF Plug-In, 0.01 to 20 GHz H.P. 83592A. A plug-in of narrower frequency range (X-band) may be selected at considerable cost savings. 83545A 5.9 12.4 GHz.

- Power Splitter H.P. 11667A

- Automatic Frequency Counter H.P. 5343A

- Source Synchronizer H.P. 5344A. Obtained as an interconnected assembly with the counter.

- Coaxial cables and adapters.

- 10 dB Attenuator H.P. 8491B

- 8.9 kN Dillon Force Gauge, Compression Model X, Part Number 381612301, with ±1% full scale accuracy.

- Vise or press that is able to exert controlled 4.45 kN force on the test fixture and that opens at least 127 mm to accept the force gauge and test fixture.

- Programmable Power Meter H.P. 436A

- Power Sensor H.P. 8484A with 70 to 10 dBm range.

- IEEE 488 (GPIB) cables

- Controlling computer with GPIB interface.

The above equipment is connected as follows as illustrated in Figure 2:

- *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.

- *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 sweeper, synchronizer, power meter, and computer interface.

- *Other connections.* The power sensor is connected to the other probe of the fixture and its special cable connects into the power meter.

- 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 3.

4.3 Automated Network Analyzer for the Test Setup
The instrumentation described in 4.1 or 4.2 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). 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 and 4.2. 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 Recommended Fixture Design An improved test fixture design is shown that facilitates changing test pattern cards and lends itself to control of temperature. The test fixture shall be constructed as shown in Figure 4 through Figure 14.

The resonator circuit shown in Figure 4 is an example of a test pattern designed for a material with a permittivity of 2.20. For other permittivity values, different pattern dimensions will be required as outlined in Table 1. It shall be defined on one side of a material of similar type to that being tested, a laminate with dielectric thickness of 0.216 mm ± .018 mm. The cladding thickness is normally specified as MF-150F designation 1 copper (nominal thickness of 0.036 mm but designation down to Q (0.010 mm) may also be used. Designation Q is preferred for high permittivity materials as covered in 4.2 and 9.7, Note. The reverse side of the circuit board has all copper removed. The copper foil shall be of IPC-MF-150, type 1, electrodeposited, type 5, wrought, or type 7, wrought-annealed. The type of copper foil and the treatment for adhesion will affect the Q measurement. The 1/Qc values in Table 1 do not take into account surface treatments or higher resistivity values for the conductor that are encountered with the specified foil types.

The test pattern card shall have a permittivity equal to the nominal value of the type being tested with a tolerance of ± 2.5% of the nominal value (measured by stacking sufficient plies to the total thickness requirement of a specimen as above. Use a photo resist and etching method capable of reproducing circuit dimensions with ± 0.025 mm tolerance. All copper shall be removed from the other side of the test pattern card. See 9.7, Note, for special treatment of ceramic-PTFE substrate types.

The pattern card of Figure 4 is 68.6 mm wide by 55.4 mm high and is designed for the fixture hardware in Figure 5 through Figure 14. The length is cut so that when the pattern card is clamped for the lap joint with the striplines on the base card, the resonator is centered in the 51 mm high area above the base plates of the fixture. For materials with permittivity values higher than the nominal 2.50 shown in Table 1, please see 5.2 for a discussion of recommended fixture modifications.

Probe line widths are based on ground plane spacing taken as twice the nominal thickness of the two specimens plus thickness of the pattern card and its 0.034 mm copper foil pattern and computed as if the stripline were centered between ground planes[1,3].

Chamfer values are based on published design curves[2].

The length of the four node resonator is given in Table 1. Resonators of lower node values for the purpose of measuring ΔL according to 6.1, will be proportionately shorter with the probe lengths modified so that the gap is the same.

The values for conductor loss, $1/Q_c$, in Table 1 are calculated from known properties of copper, the test frequency, the calculated characteristic impedance of the section of stripline comprising the resonator, and its cross-sectional geometry using published formulas[1]. The values shown are usually biased low giving a high bias to loss tangent results, because conductor actually used may not have a smooth surface and may include oxides, microvoids, or other sources of higher resistivity.

5.2 Fixture Modifications for High Permittivity Materials Modification of the fixture design of Figure 5 through Figure 14 and pattern card dimensions in Figure 4 are recommended to overcome problems experienced with extraneous transmissions and resonances at frequencies near the desired resonant peak.

5.2.1 Replace the coax-stripline launcher shown in Figure 7. The part suggested has a tab width of 1.27 mm and may be replaced with Omni-Spectra Part No. 2070-5029-02, or equivalent, intended for 1.57 mm ground plane spacing and with a tab width of 0.635 mm. A further acceptable alternative is to redesign the base plates to accept another type of coaxial fitting such as a flange mount jack, which can be modified to provide a smooth, low-reflection transition from 3.0 mm semirigid cable with Z_O = 50 Ohm, low permittivity insulation into stripline with Z_O = 50 Ohm, and high permittivity insulation in the fixture.

5.2.2 If the stripline launcher in 5.2.1 is used, the edge at the step to accommodate the launcher body on the base plate should be machined with a slight undercut for an acute included angle of about 80°. This, combined with a means to press the launcher body axially against the edge, will assure a well-defined ground connection from coax to stripline. A poorly defined ground connection with ground current path length varying or longer than that of the signal conductor has been found to give rise to scattering, reflections, and resonances in the open ended probe line that are evident as extraneous fixture transmissions that may distort the resonant peak to be measured.

5.2.3 Omit the conductor lap joints but keep the extended base cards in the fixture assembly. See figures 13 and 14.

With high permittivity materials, the lap joint also gives rise to unwanted scattering, reflections, and resonances in the open-ended probe line, as discussed in 5.2.2. For this purpose the resonator pattern card will have a longer vertical dimension to extend down to the launcher pin replacing the spacer board in Figure 13. It should still center the resonator in the clamping block area. The base dielectric boards will be etched free of metal. The ground plane foils will also extend down to the launcher.

The feature of extending the base dielectric boards upward above the base plates is to be retained as a means to prevent premature damage to the resonator pattern card with repeated loading and unloading of the fixture. The base plate with the deeper step will be on the side toward which the resonator pattern faces to avoid straining the offset launcher tab during assembly.

5.2.4 Scale down the fixture dimensions to move remaining probe line resonances away from the resonant frequency of interest. For ε_r = 10.5 material, the following dimensions were found effective.

Table 1   Dimensions for Stripline Test Pattern Cards in Millimeters

Nom. ε_r	Nom. Thk.	Pattern Card Thk.	Probe Width	Chamfer X, Y	Probe Gap	Resonator Width	Resonator Length 4 Node	$1/Q_C$ Conductor Loss
2.20	1.59	0.22	2.74	3.05	2.54	6.35	38.1	0.00055
2.33	1.59	0.22	2.67	2.92	2.54	6.35	38.1	0.00055
2.50	1.59	0.22	2.49	2.79	2.54	6.35	38.1	0.00055
3.0	1.59	0.22	2.13	2.41	2.54	5.08	31.8	0.00058
3.5	1.59	0.22	1.85	2.16	2.54	5.08	31.8	0.00058
4.0	1.59	0.22	1.62	1.93	2.54	5.08	31.8	0.00058
4.5	1.59	0.22	1.45	1.73	2.54	5.08	31.8	0.00058
6.0	1.59	0.22	1.07	1.30	2.29	3.81	25.4	0.00062
6.0	1.27	0.22	0.86	1.07	2.29	3.81	25.4	0.00072
10.5	1.27	0.22	0.41	0.54	2.03	2.54	17.3	0.00079

Standard clamp force for all the above is 4.45 ± 0.22 kN

	mm
Height of base plate from step to top edge	8.53
Height of clamp block and specimen	25.4
Height from launcher body to resonator center line	21.23
Width of clamp block and specimen	55.9
Horizontal center line distance between probe lines	30.5
Probe length from launch to gap	25.81

5.2.5   Thinner copper cladding (weight Q) for the resonator pattern card is recommended as mentioned in 5.1. If weight Q is used, the embedding process discussed in note 9.7 can be avoided. Experience has indicated that this reduction in thickness has not impaired the loss tangent values obtained by the method.

5.3 Older Fixture Design   An older acceptable alternate test fixture design is shown in Figure 15. This is included since fixtures of this type are in service at various laboratories. Compared to 5.1, fixtures of this design depend on ambient conditions for temperature control. Changing resonator test pattern cards is less convenient.

5.4 Temperature Control   It is a well-known fact that PTFE and composites containing it show a room temperature transition in the crystalline structure that produces a step-like change in the permittivity. This temperature region should be avoided.

Normally, control of ambient temperature is adequate for routine measurements. A means other than ambient temperature to control fixture temperature facilitates collecting data on the variation of permittivity with temperature. With the test fixture of 5.1., use 6 mm inside diameter tubing for circulating fluid to control temperature. The following items are needed to complete the temperature control system.

5.4.1   Laboratory Immersion Heating Bath/Circulator, such as Haake Model D1, Lauda Model MT, or equivalent and a small capacity bath. The Immersion Heating Bath/Circulator shall be connected to the clamping blocks in series with a return line to the bath.

5.4.2   Two fine diameter thermocouple probes with leads and suitable instrumentation for readout or recording of temperature. A digital thermometer, such as Ohmega Model DSS 115 or equivalent, is used for monitoring temperature.

6.0 Measuring Procedure

6.1 Preparation for Testing   The actual length of the resonator element shall be determined by an optical comparator or other means capable of accuracy to 0.005 mm or smaller.

Unless otherwise specified, specimens shall be stored before testing at 23°C + 1-5°C/50% ± 5% relative humidity (RH). 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 4.2, 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 4.2 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.

The temperature of the test fixture shall be in the range of 22°C to 24°C, unless otherwise specified. If this standard temperature is to be used and the temperature of the fixture is to be controlled by the ambient conditions in the testing laboratory, then the laboratory shall be maintained at 22°C to 24°C and the fixture shall be stored in the laboratory for at least 24 hours prior to use.

If non-standard temperature is specified and the fixture of 4.1 is used with the temperature control apparatus described in 4.2, then the rest of this paragraph applies. Prior to making electrical measurements, the circulator is started and adjusted to within 1°C of the desired test temperature. The time required for stabilization depends on the specific temperature control apparatus in use, the size of the circulation bath tank, and the temperature selected. Additional stabilization time will be required for each specimen to come to the set temperature after it has been clamped in the fixture.

The test fixture containing the test specimens shall be placed in the clamping fixture and the specified force of 4.45 ± 0.22 kN is applied through the calibrated force gauge to the 1290 mm^2 area centered directly over the resonant circuit as shown in the assembly of Figure 12, Figure 13, or Figure 15.

6.2 Manual Measurement of the Specimen The following procedure is applicable where equipment as described in 4.1 is available. The equipment of 4.2 could also be operated manually. The stripline resonator formed by the fixture pattern card and ground planes with the specimen cards inserted is referred to as a cavity. The sweep oscillator is referred to here as the sweeper.

6.2.1 Determination of Cavity Resonant Frequency The resonant frequency of the circuit shall be found by scanning the sweeper over the expected transmission range of the test resonator. The sweeper shall be precisely adjusted to the frequency that produces a maximum reading of the SWR Meter No. 1. The frequency meter shall then be adjusted for a minimum reading of the SWR Meter No. 2. Record the resonant frequency. The input selector of the SWR Meter No. 1 should be set for low impedance input for proper square law detection.

6.2.2 Determination of Cavity Half-Power Points With the incident signal having been set to maximum resonator

transmission, adjust the gain of the SWR Meter No. 1 until the meter reads 0 dB. The frequency of the sweeper shall then be adjusted to give 3 dB readings both above and below the maximum transmission frequency. Measure each frequency with the frequency meter and record the results:

• f1: above the maximum transmission frequency

• f2: below the maximum transmission frequency

6.3 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 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 following sequence of steps 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.

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

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

6.3.3 The computer checks the synchronizer for status until the status value drops to zero, indicating the frequency is locked.

6.3.4 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.

6.4 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 and 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 downward 3 dB.

6.4.1 The first option is to get the three points (f_r, f_1, and f_2) as described in 6.2 and 6.3. 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 are 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.

6.4.2 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 statistically determine values for Q, f_r, and dB_r that best fit the F_i, dB_i paired data points to the formula.

$$dB_i = dB_r - A \log_e (1 + 4 Q^2 ((f_i / f_r - 1)^2)$$

where

$A = 10 \log_e (10) =$ constant for converting from $\log_e$ to dB

This formula may be derived from combining equation 4 and equation 6 as corrected in 7.2, 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 equation 2 of 7.1 and equation 4 of 7.2 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[5].

7.0 Calculations

7.1 Stripline Permittivity 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:

$$\varepsilon_r = [n C / (2 f_r (L + \Delta L))]^2 \qquad [1]$$

Where n is the number of half wavelengths along the resonant strip of length L, 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 $3.000 \cdot 10^{11}$ mm/s, and f_r is the measured resonant (maximum transmission) frequency.

The more exact value for C of $2.9978 \cdot 10^{11}$ mm/s would give a lower permittivity value, differing for example by 0.003 for 2.5 permittivity material. This method does not use the more exact value to avoid confusion with specifications for materials and proven component designs based on older versions of this method where $3.000 \cdot 10^{11}$ has been in use.

For example, for a specified 38.1 mm long resonator, the parameters at X-band are n = 4, L = 38.1 mm. For a given material with ΔL = 1.397 mm, the formula for ε_r becomes:

$$\varepsilon_r = 2.30764 \cdot 10^{20} / f_r^2 \qquad [2]$$

7.1.1 Determination of L ΔL, a correction for the fringing capacitance at the ends of the resonator element, is affected by the value of the ground plane spacing and the degree of anisotropy of permittivity of the material being tested. The degree of anisotropy is affected by the amount and orientation of fiber and the difference between permittivity of fiber and matrix polymer. Because of this, a ΔL value for use with a particular type of material must be determined experimentally by the following procedure.

7.1.1.1 Prepare a series of resonator circuit cards having patterns in which only the resonator element length is varied to provide n values of 1, 2, 3, and 4 at close to the same frequency. For example, lengths of 9.5 mm, 19.0 mm, 28.6 mm, and 38.1 mm may be used.

7.1.1.2 For each of at least three sets of typical specimen pairs of the material to be measured, measurements of f_r are obtained at each L value. Plot L f_r/n on the Y axis versus f_r/n on the X axis or preferably use a numeric linear regression analysis procedure to determine the slope of the least squares fit through the four data points. The slope is equal to the negative value of ΔL.

7.1.1.3 The ΔL values for each of the specimen pairs may then be averaged to provide a suitable working ΔL value. For a given material type, a ΔL value should be agreed upon as standard for testing to a specification.

7.1.2 Determination of Effect of Specimen Thickness on L The ΔL correction for end fringing capacitance will vary

with specimen thickness, increasing as specimen thickness increases. Ignoring this effect by use of a fixed ΔL value for calculating test results will bias the permittivity values upward for thicker specimens, downward for thinner ones. For low permittivity materials where the resonator is longer, this bias is quite small and only of interest for close tolerance applications. For high permittivity materials, the smaller resonator length makes this correction more important.

There are two ways in which this thickness effect may be handled: by an empirical determination of ΔL for various thicknesses or by assuming a proportionality to the published prediction of ΔL[(4)].

7.1.2.1 For the empirical method, use the 7.1.1 procedure to obtain ΔL with specimens at extremes of thickness variation expected in day to day testing. Use numerical linear regression of the collected ΔL-specimen thickness data pairs to derive a linear formula of the form

$\Delta L = B0 + B_1 \text{ (thickness)}$

Specification values for B_O and B_1 for a given material must be agreed upon for a particular material type.

7.1.2.2 A ΔL correction factor can be derived for a given material type in a range of permittivity values by determining for specimens of known thickness the ratio of ΔL derived according to 7.1.1 to that predicted by equation 3 when R=1. An average of ratios so determined must be agreed upon as the specified correction factor for the formula. From this, ΔL is calculated by:

$$\Delta L = R (K^2 + 2 K W) / (2 K + W) \qquad [3]$$

where

R = the average ratio of observed to predicted ΔL

K = $B \log_e (2) / pi$

= 0.2206356 B

W = width of resonator in mm

B = 2 (specimen thickness) + (test pattern card thickness)

= total ground plane spacing in mm

7.2 Calculation of Effective Dielectric Loss Tangent A value for loss tangent for the dielectric is obtained by subtracting the appropriate conductor loss value, $1/Q_c$, in Table 1 from the total loss value, $1/Q$, as shown

$$\tan \delta = 1/Q - 1/Q_c \qquad [4]$$

or

$$\tan \delta = [(f_1 - f_2) / f_r] - 1/Q_c \qquad [5]$$

where

$1/Q$ or $(f_1 - f_2) / f_r$ is the total loss due to the dielectric, copper, and copper-dielectric interface.

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

$$\tan \delta = (1 - (f_1 / f_r)) (10^{(dB_1/10)} - 1)^{-0.5} +$$
$$((f_2 / f_r) - 1) (10^{(dB_2/10)} - 1)^{-0.5} - (1/Q_c) \qquad [6]$$

dB_1 is the dB below the peak power level at f_1

and

dB_2 is the dB below the peak power level at f_2

7.2.1 Calculation of $1/Q_c$

The following calculation scheme is used[(1)]

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

where

α_c = $4 R_s \varepsilon_r Z_O Y / (377^2 B)$

= attenuation constant, nepers/mm

R_s = $0.00825 f^{0.5}$ = surface resistivity of copper, Ohm

Z_O = $377/(4 \varepsilon_r^{0.5} (C_f + (W/(B - T))))$

= characteristic impedance of resonator, Ohm

377 = $120 \pi.$ = 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 = $B / (B - T)$

ε_r = nominal permittivity

B = ground plane spacing, mm

C = 299.796 mm/ns = speed of light

f = nominal resonant frequency, GHz

NOTE: GHz is equivalent to cycles/ns to keep units consistent in this section 7.2.1.

W   =   resonator width, mm

T   =   resonator conductor thickness, mm

Where combinations of resonant frequency, resonator width, ground plane spacing, and nominal permittivity are encountered other than those listed in Table 1, a calculated $1/Q_c$ must be agreed upon. Data is not currently available for correcting this calculated value to account for increased conductor loss due to surface treatments or type of copper foil used.

7.2.2 Corrections to the Loss Factor   Corrections in the total loss value, 1/Q, may be needed for materials of high anisotropy of ε_r as mentioned in 1.2.2. The Q actually measured is Q_{loaded}, but is often assumed to be $Q_{unloaded}$. The probe gap given in Table 1 is intended to provide insertion loss at a resonance high enough to make Q_{loaded} approximately equivalent to $Q_{unloaded}$.

When materials with high anisotropy of permittivity are measured, probe coupling is affected and the insertion loss becomes small, making a correction useful before applying the above calculations. Insertion loss is determined by comparing transmitted power at resonant frequency of the fixture and specimen with the resonator pattern card and with a similar card having a straight through 50 Ohm line. The dB_r difference as dB_r is related to the power ratio by

$$P_2 / P_1 = e^{(\log_e(10) \, dB_r \, / \, 10)} \qquad [8]$$

and the unloaded Q is determined from the measured Q by

$$Q_{unloaded} = Q_{loaded} / [1-\sqrt{P_2 / P_1}] \qquad [9]$$

The following values illustrate this relationship:

dB_r	60	50	40	30	20	15	10	5
$Q_{unloaded}$/ Q_{loaded}	1.00	1.00	1.01	1.03	1.11	1.22	1.46	2.28

8.0 Report   The report shall contain the following:

• The measured length of the resonator and ΔL value.

• The measured thickness of specimen stacks.

• The maximum transmission (resonant) frequency, f_r.

• If the three point method of 6.2, 6.3 or 6.4.1 is used, report the frequencies of the two 3 dB points on the resonance curve or the frequency and actual dB value of the two points.

• If the non-linear regression (NLR) method of 6.4.2 is used, then optionally report the number of data points used, NLR uncertainty values for f_r, Q_{loaded}, dB_r

• The calculated effective stripline permittivity.

• The calculated effective dielectric loss tangent.

• If the test was not done in the X or machine direction, give the direction in which test was performed. That is, orientation of the resonator with respect to the X or Y axis of the specimen.

• The temperature of the test fixture during the test.

• The grade of copper foil used in the test pattern card.

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. In this method, a great saving in time and cost of testing is achieved by using a permanent stripline resonator, which is part of the test fixture. With this fixture, variations in loss tangent due to the dielectric can be monitored but not the additional loss due to the type of metal and bonding treatment used in laminating.

9.3 Measurements at Other Frequency Bands   The test equipment of 4.1 can be modified for L, S, and C band measurements at some additional cost. The test equipment of 4.2 will be able as is to handle other bands.

9.4 Frequency Ranges   Accepted frequency ranges for the various bands are:

L   1.12 1.70 GHz

S   2.60 3.90 GHz

C   3.95 5.85 GHz

X   8.00 12.40 GHz

9.5 Other Metal-Clad Dielectrics This method can be adapted for measurements of other metal-clad dielectric materials. ΔL must be determined for each new material. Materials that are not somewhat compliant may yield significant errors due to air gaps resulting from the conductor thickness of the resonator.

9.6 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.

9.7 High Permittivity Soft Substrates Soft substrates consisting of PTFE highly filled with ceramic filler require additional steps in the preparation of resonator pattern cards to embed the conductor pattern into the substrate so that thickness of the card is uniform and the same in both the pattern and non-pattern areas.

The following embedding procedure is needed when the resonator pattern card has copper foil cladding of IPC-MF-150, designation 1. If the weight of the foil is reduced to Q (0.010 mm), as recommended in 4.2.5 and mentioned in 5.1, then the embedding procedure is not needed and consistency of fixture performance with pattern card replacements is improved. It appears that a soft substrate specimen is able to accommodate the thinner pattern without excessive stress concentration and bias in permittivity value.

When this preparative step is omitted or inadequately done for designation 1 copper, it has been observed that for a given resonator pattern card in the fixture, there will be a bias in the permittivity value observed. For a specimen held in the fixture for a period of time, there will be an initial high bias that drifts downward over a period of several hours. When removed, the specimen will have an embossed image of the resonator pattern. When repeated testing is done among several specimens with comparatively short clamp times of one or two minutes before reading resonant frequency, the bias is initially high and then decreases with frequency of test runs. This drift in performance is observable when reference specimens are repeatedly tested.

This drifting bias is believed to be due to the concentration of the clamp force to the smaller resonator area used for these materials combined with their higher degree of conformance. Initially, the clamping excessively compresses material on both sides of the resonator element raising its permittivity. With time, the material in both pattern card and specimen conforms by deformation flow away from the high stress area so that the bias decreases.

Use a card with embedded pattern leads to distribute stress more evenly over the specimen for little or no drift in bias. Embedding is done by clamping the pattern card between stainless steel or aluminum foil release layers between accurately planar metal blocks at about 0.69 to 1.38 MPa, while heating the blocks above the polymer melt point long enough to allow permanent conformance followed by cooling and declamping.

10.0 References

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

2. *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, Matthaei, G. L.; Young, L.; and Jones, E. M. TMcGraw Hill (1964): 206.

3. *Characteristic Impedance of the Shielded- Strip Transmission Line*, Cohn, S. B., IRE Trans MTT, (July 1954): 52 57.

4. *Discontinuities in the Center Conductor Strip Transmission Line*, Altschuler, H. M. and Oliner, A. A IRE Transactions MTT 8, (May 1960): 328.

5. *The NIST 60-Millimeter Diameter Cylindrical Cavity Resonator: Performance Evaluation for Permittivity Measurements, NIST Technical Note 1354*, Vanzura, E. J., Geyer, R. G. and Janezic, M.D, August 1993, National Institute of Standards and Technology, Boulder, CO 80303-3328.
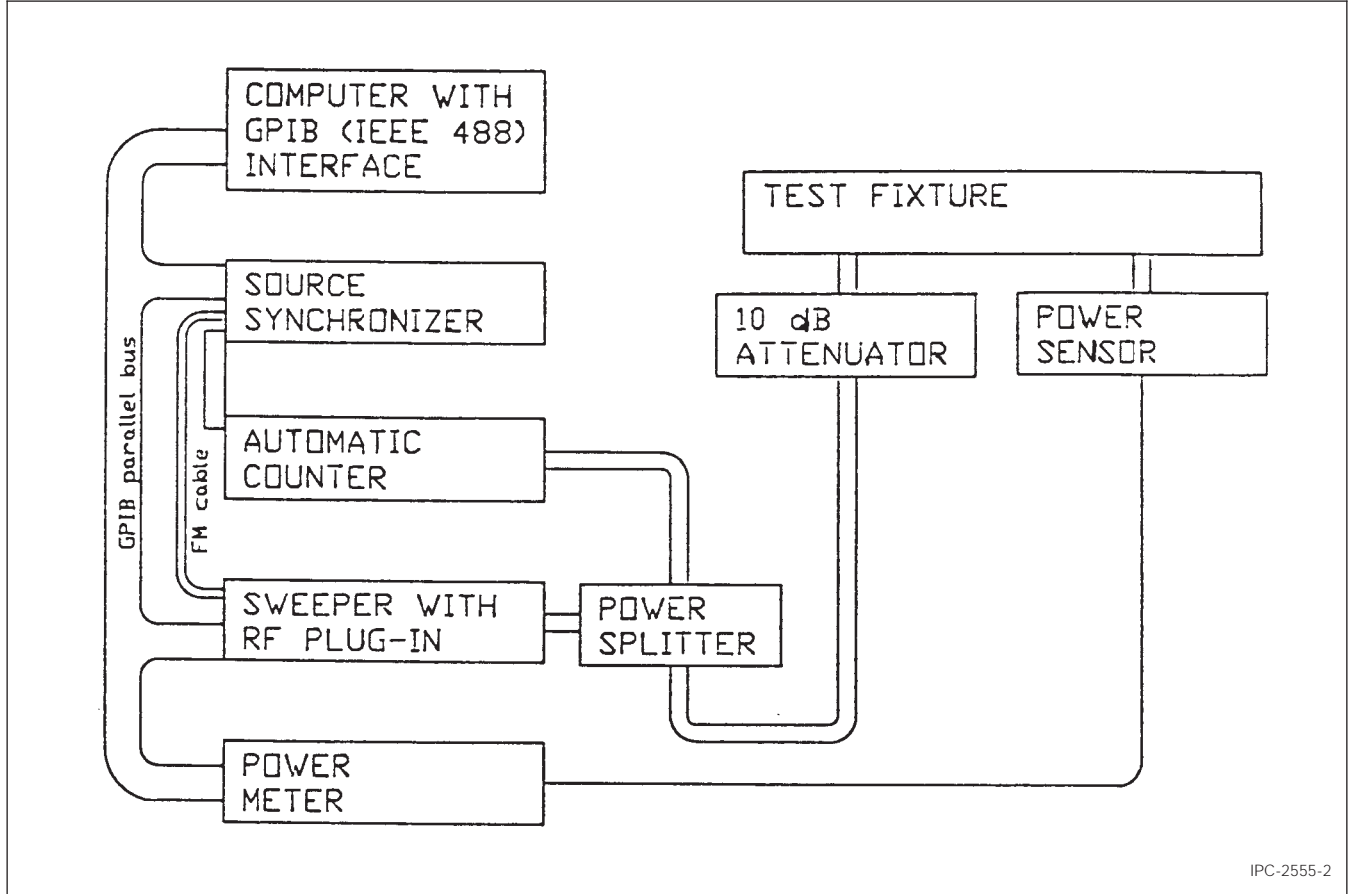
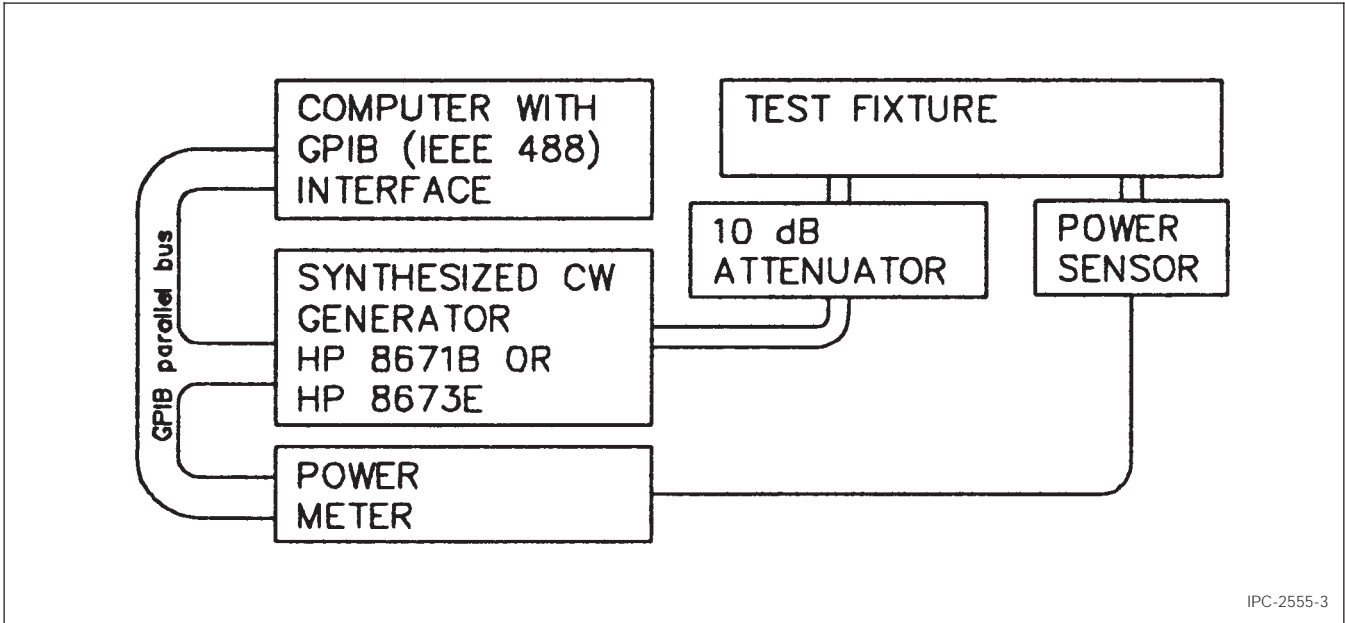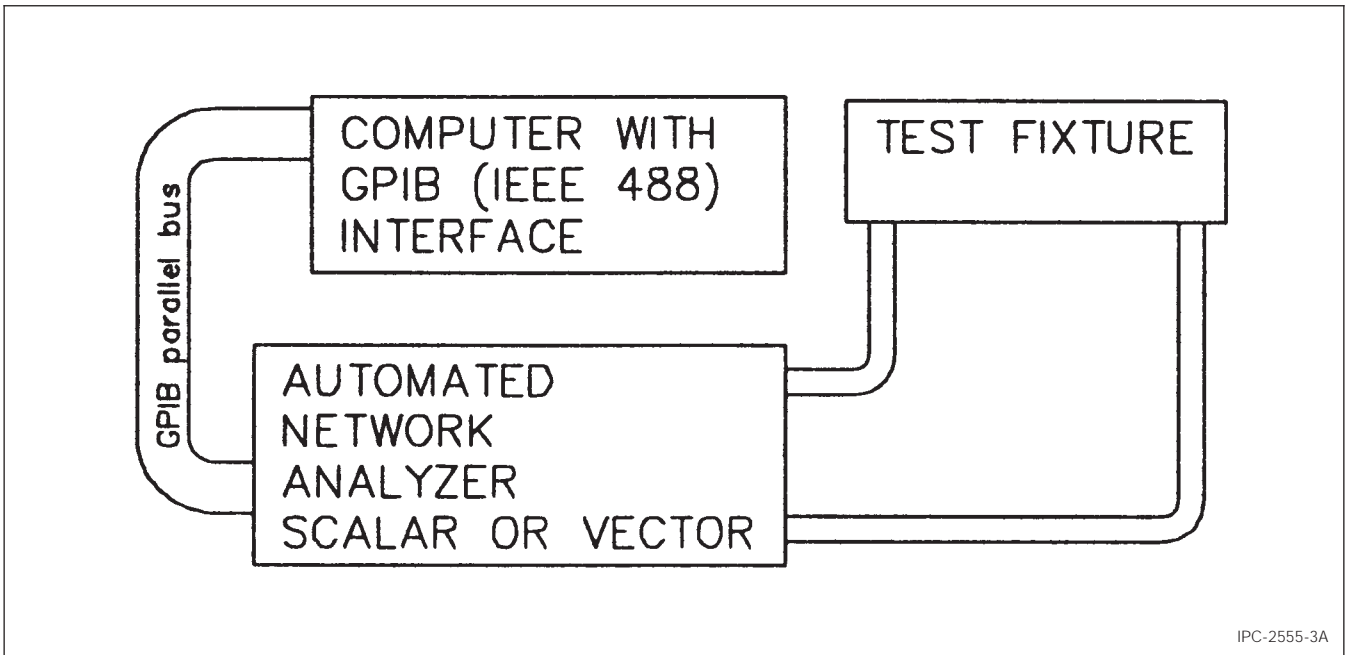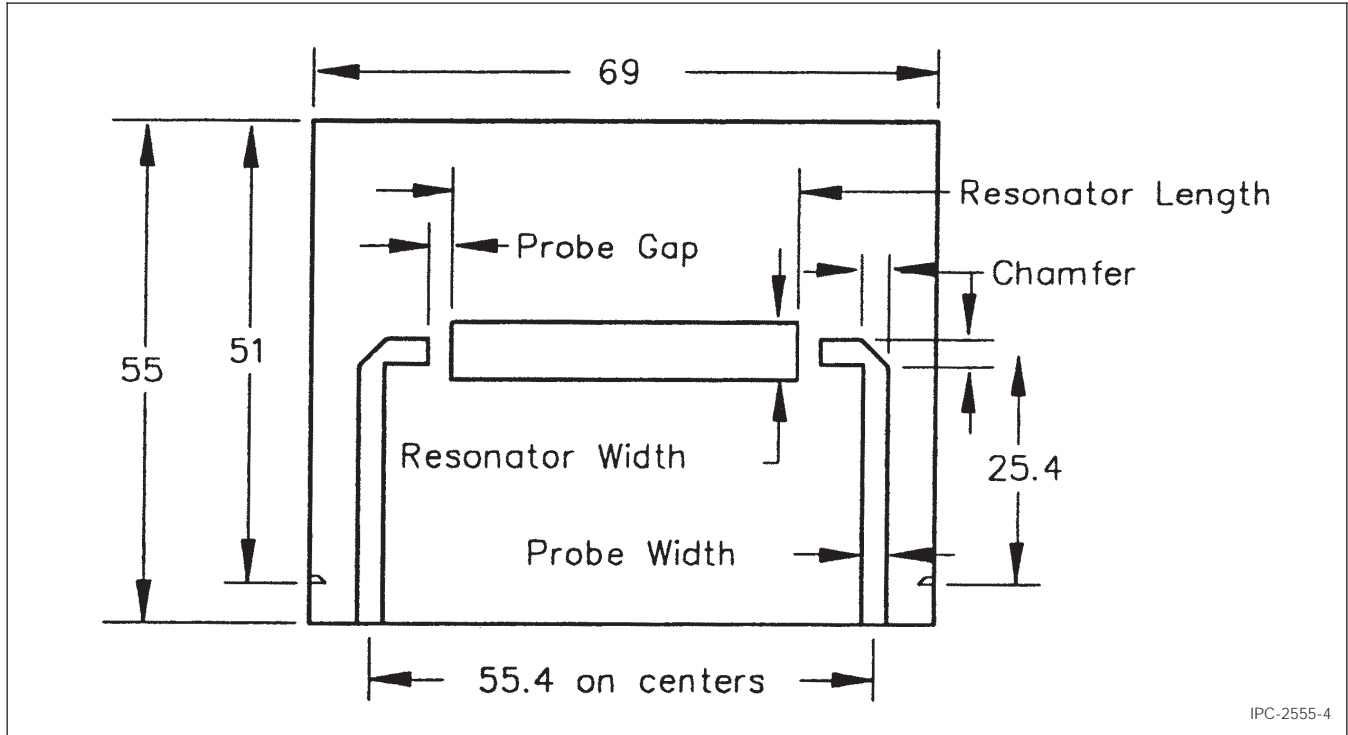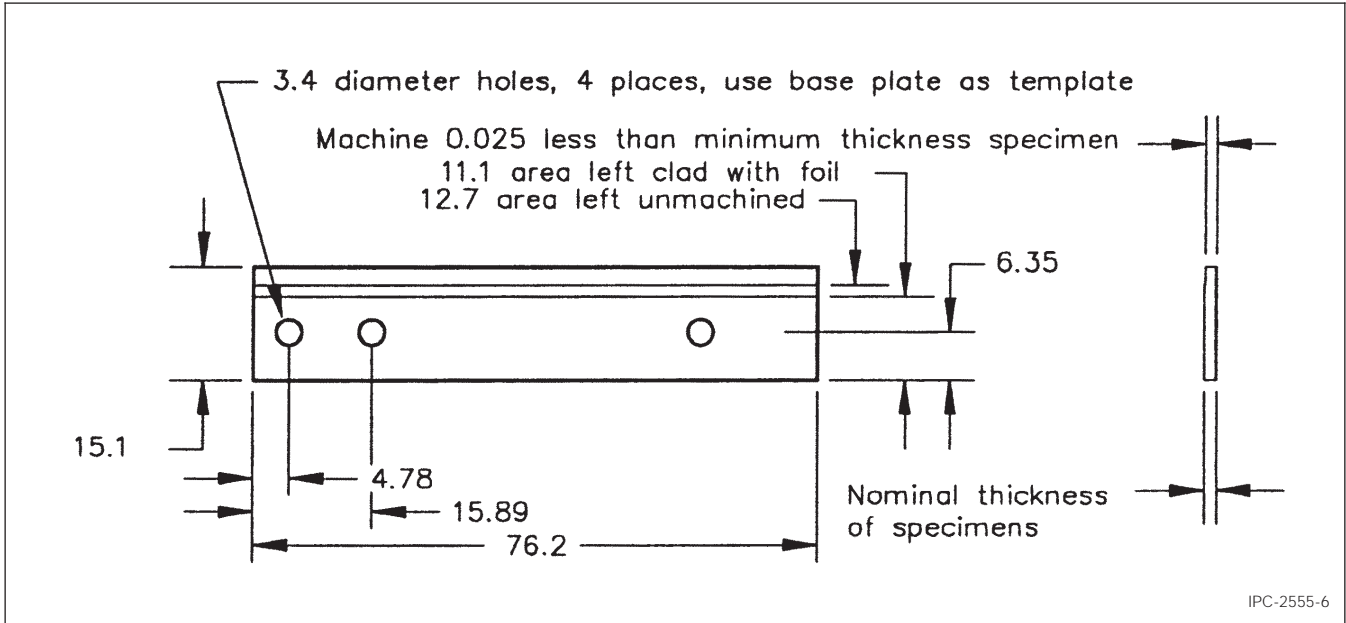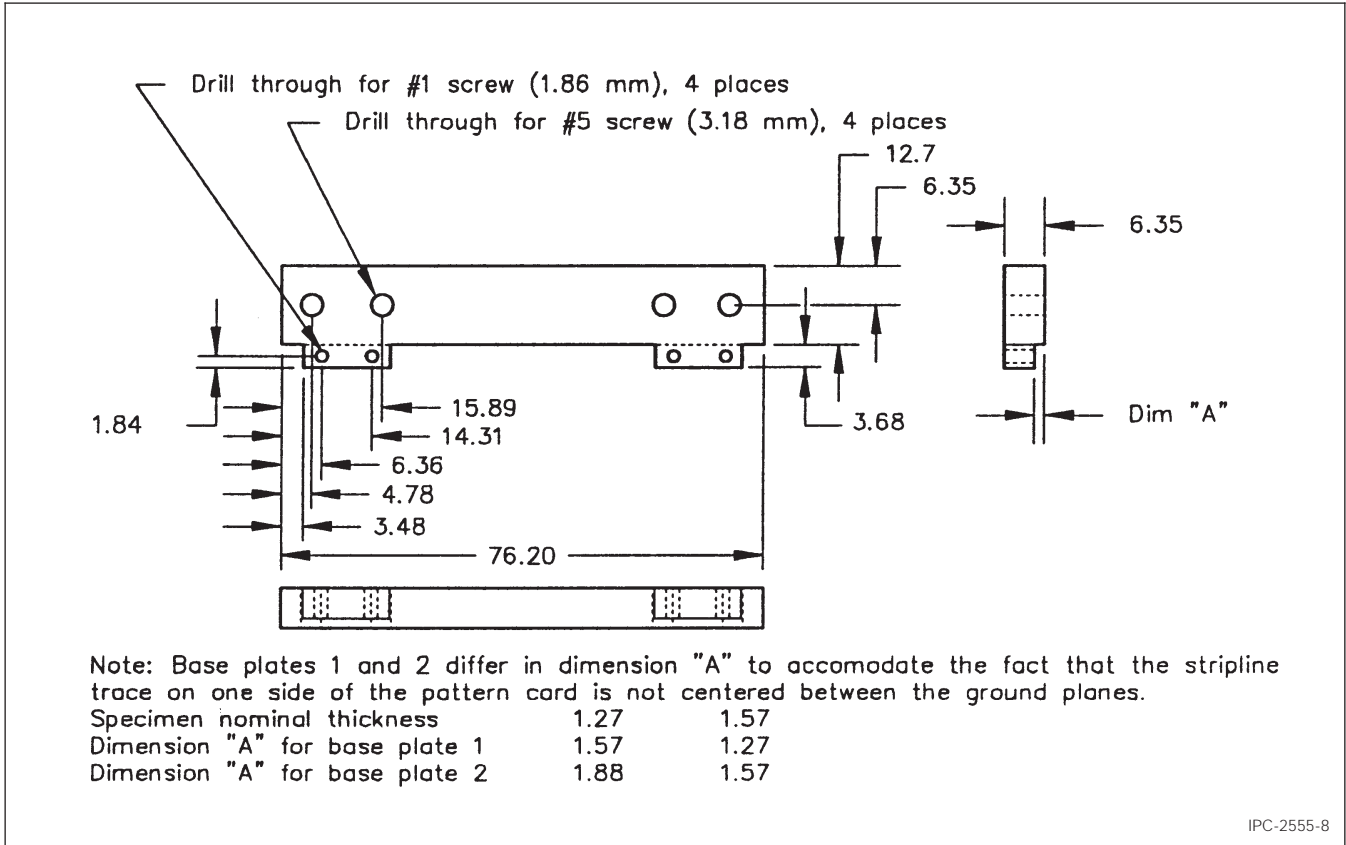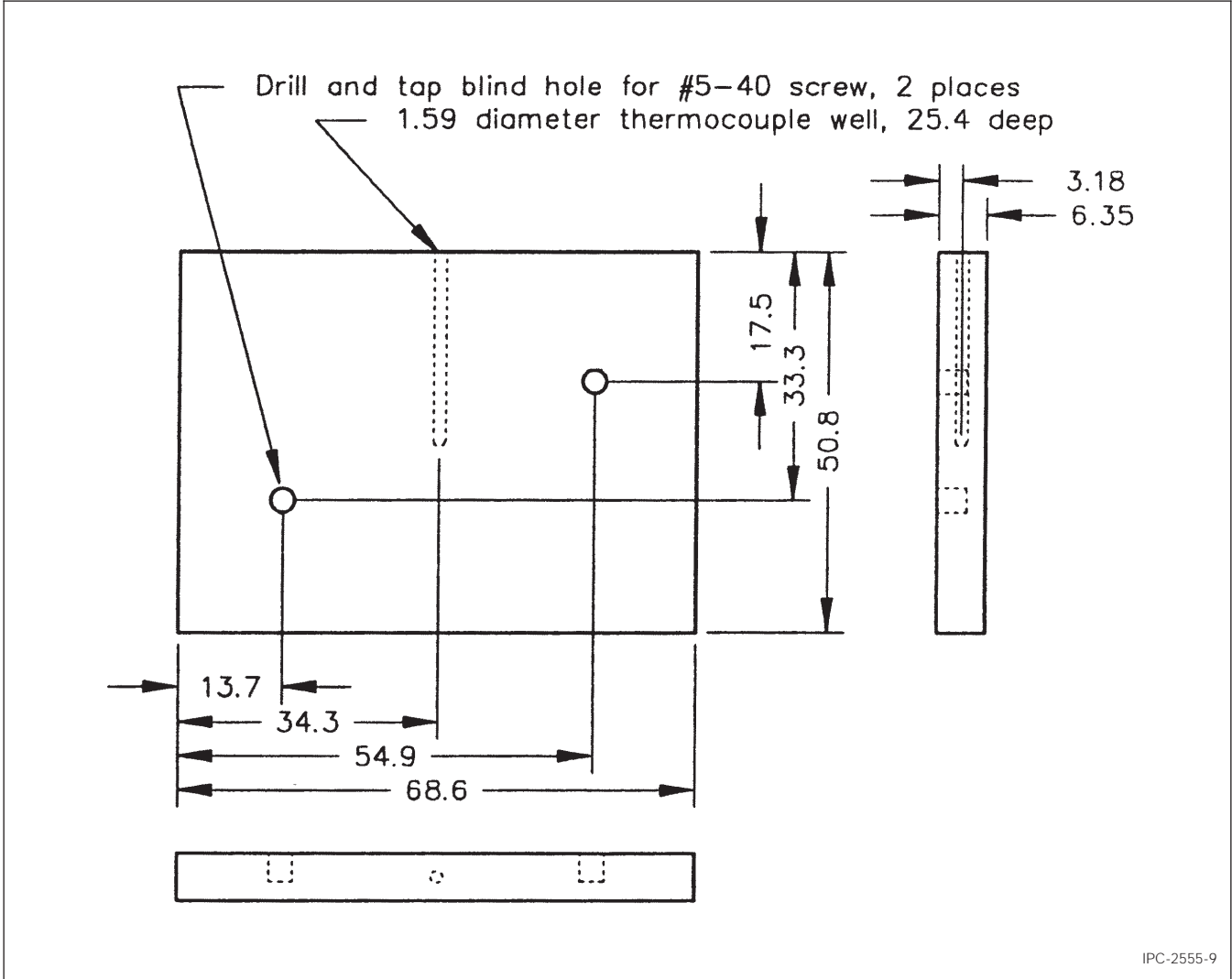|	IPC-TM-650	
Number **2.5.5.5** Revision **C**	Subject **Stripline Test for Permittivity and Loss Tangent (Dielectric Constant and Dissipation Factor) at X-Band**	Date **3/98**

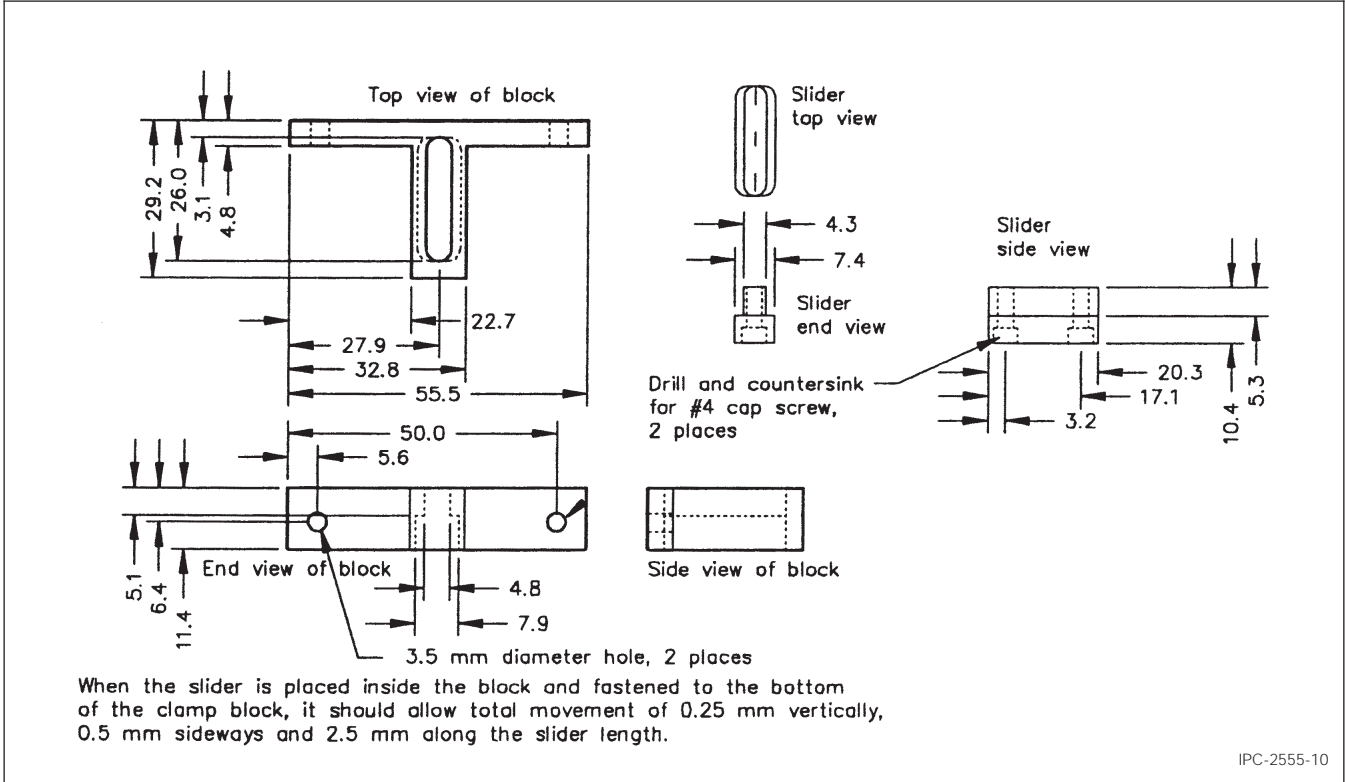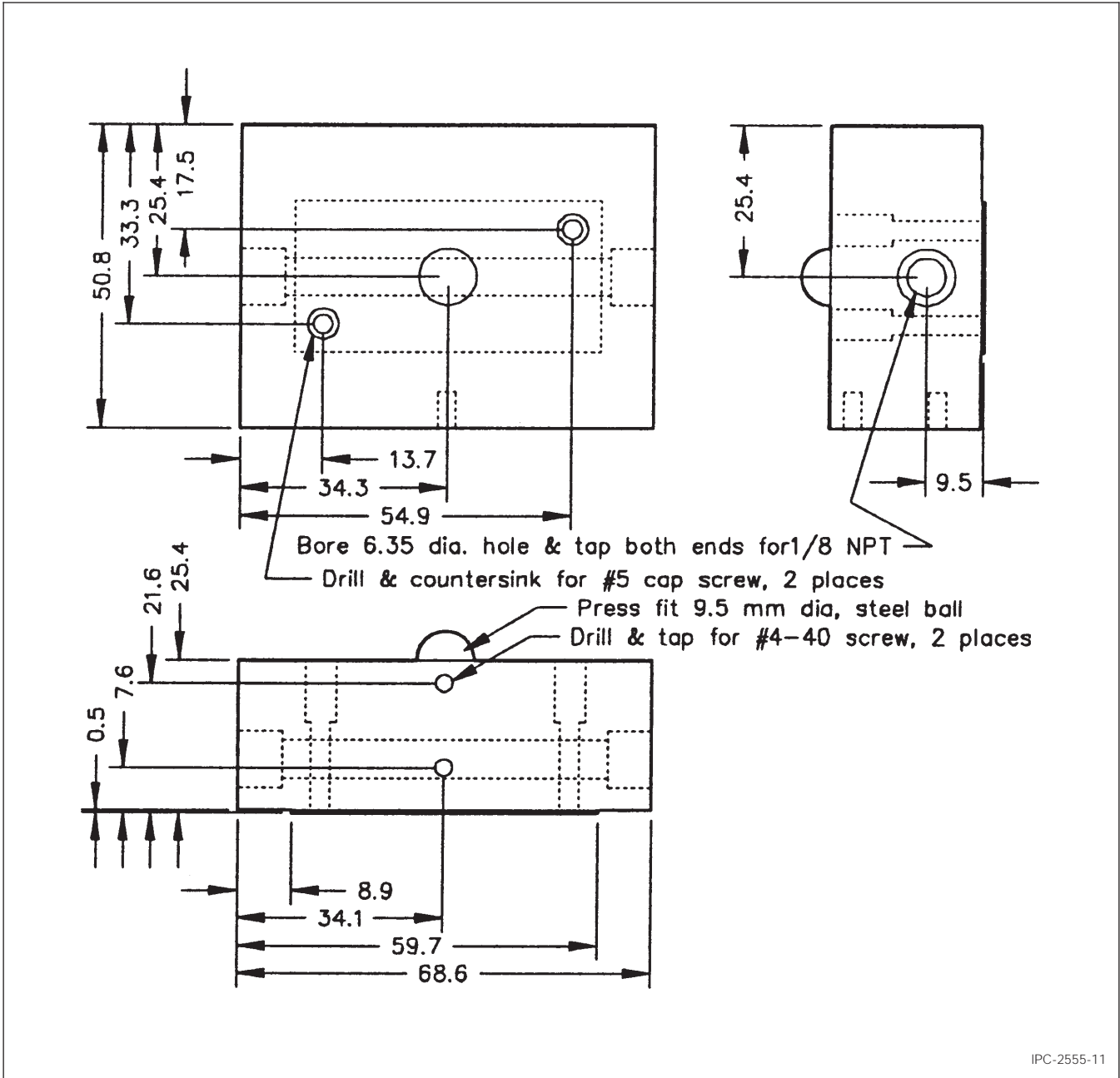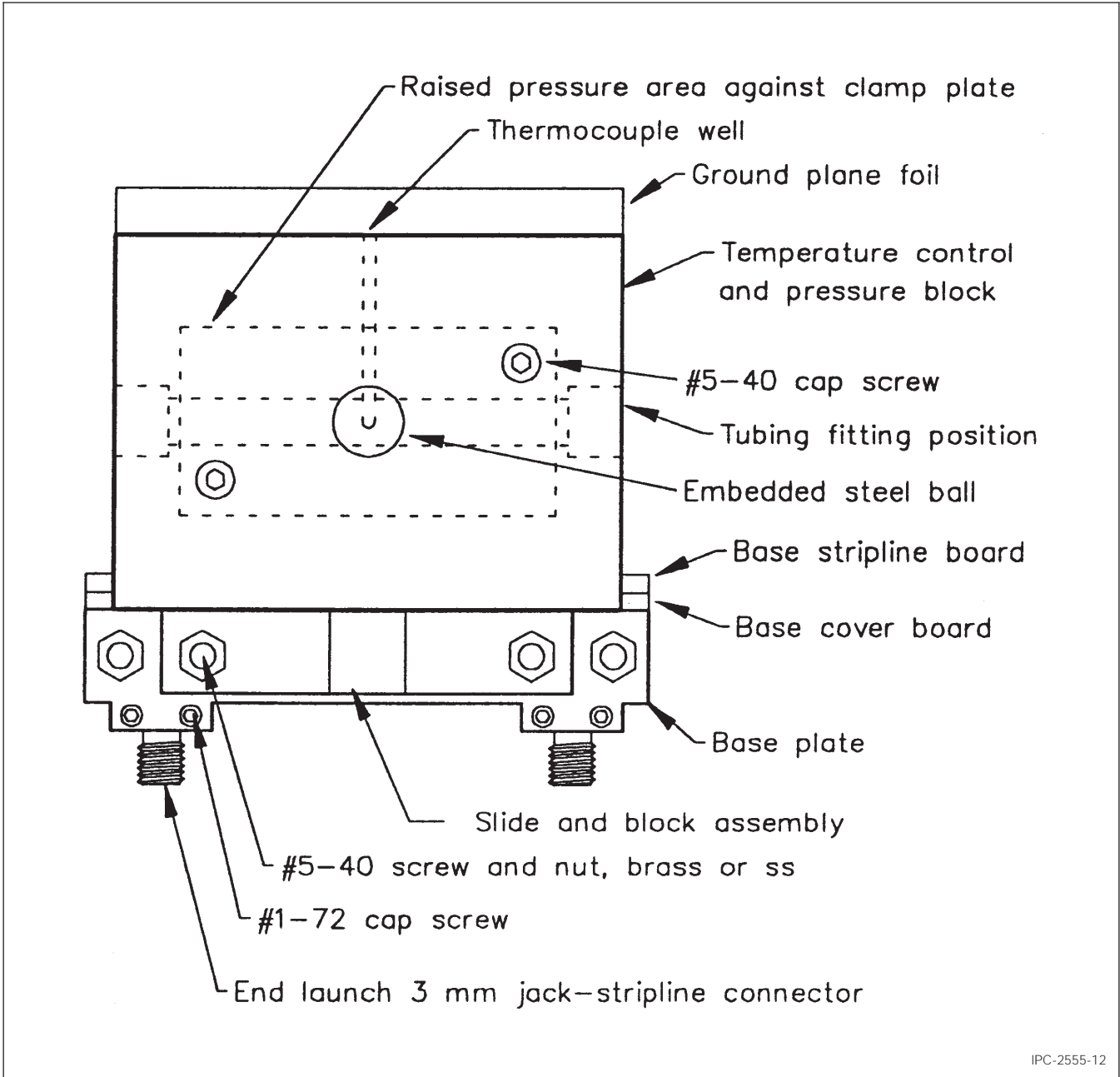**Figure 1   X-Band Permittivity Test Setup**

Figure 2   Automated Permittivity Test Setup

Figure 3   Simplified Automated Permittivity Test Setup

Figure 3A   Automated Network Analyzer for Permittivity Test Setup

Figure 4   Generalized Resonator Pattern Card Showing Dimensions of Table 1 and Made of Laminate Matching the Nominal Permittivity of Material to be Tested

Figure 5   Base Stripline Board with Copper Foil and Dielectric Matching the Nominal Permittivity of the Material to be Tested

Figure 6   Base Cover Board with Copper Foil Ground Plane

Figure 7   Detail of the Supplied Launcher Body, Omni-Spectra Part No. 2070-5068-02 or Equivalent

Figure 8   Brass or Aluminum Base Plate for Clamping the Base Cards and Connecting Launcher Bodies to the Base Card

IPC-2555-9

Figure 9   Aluminum Clamping Plate Provided with Tapped Holes for the Pressure Block and a Thermocouple Well

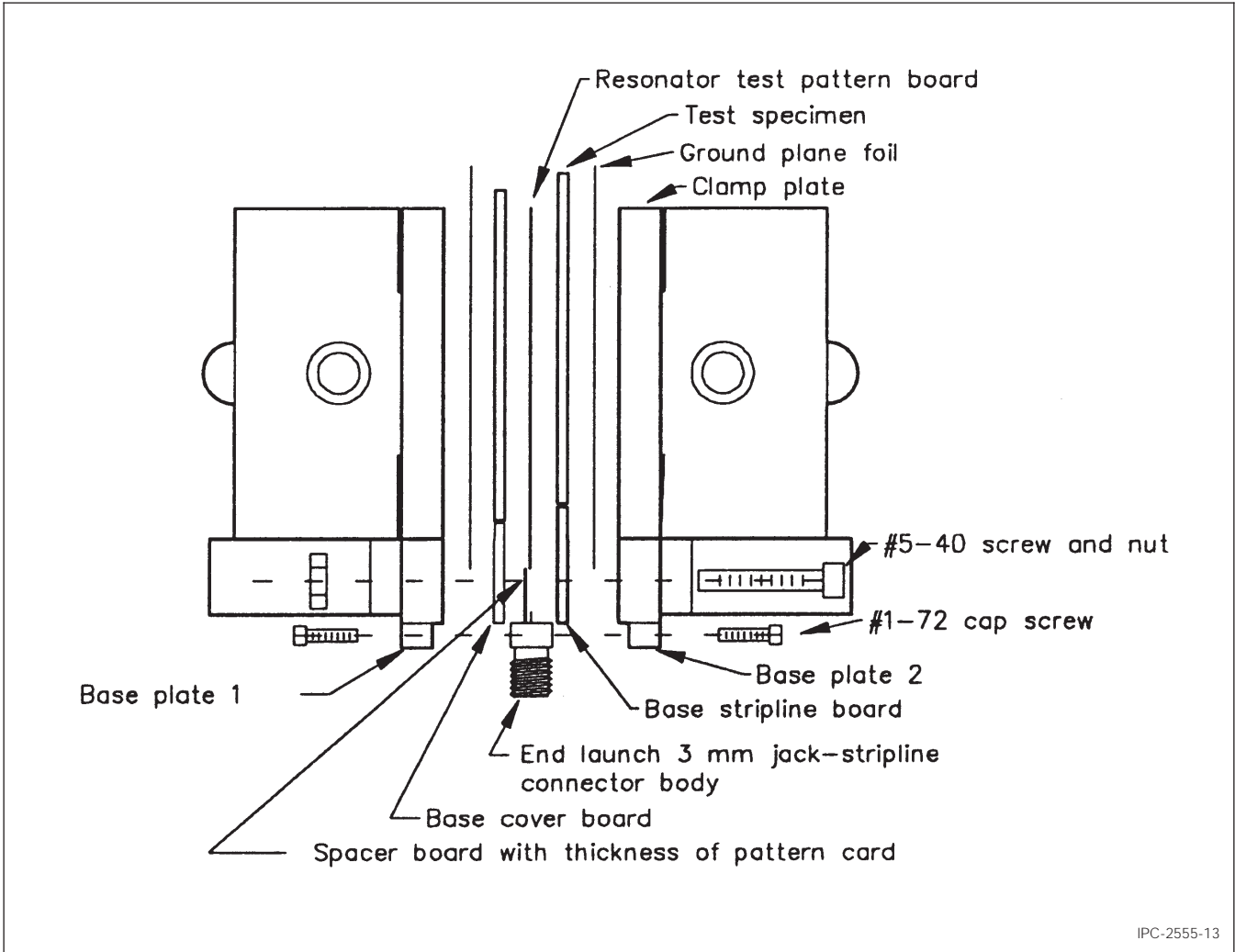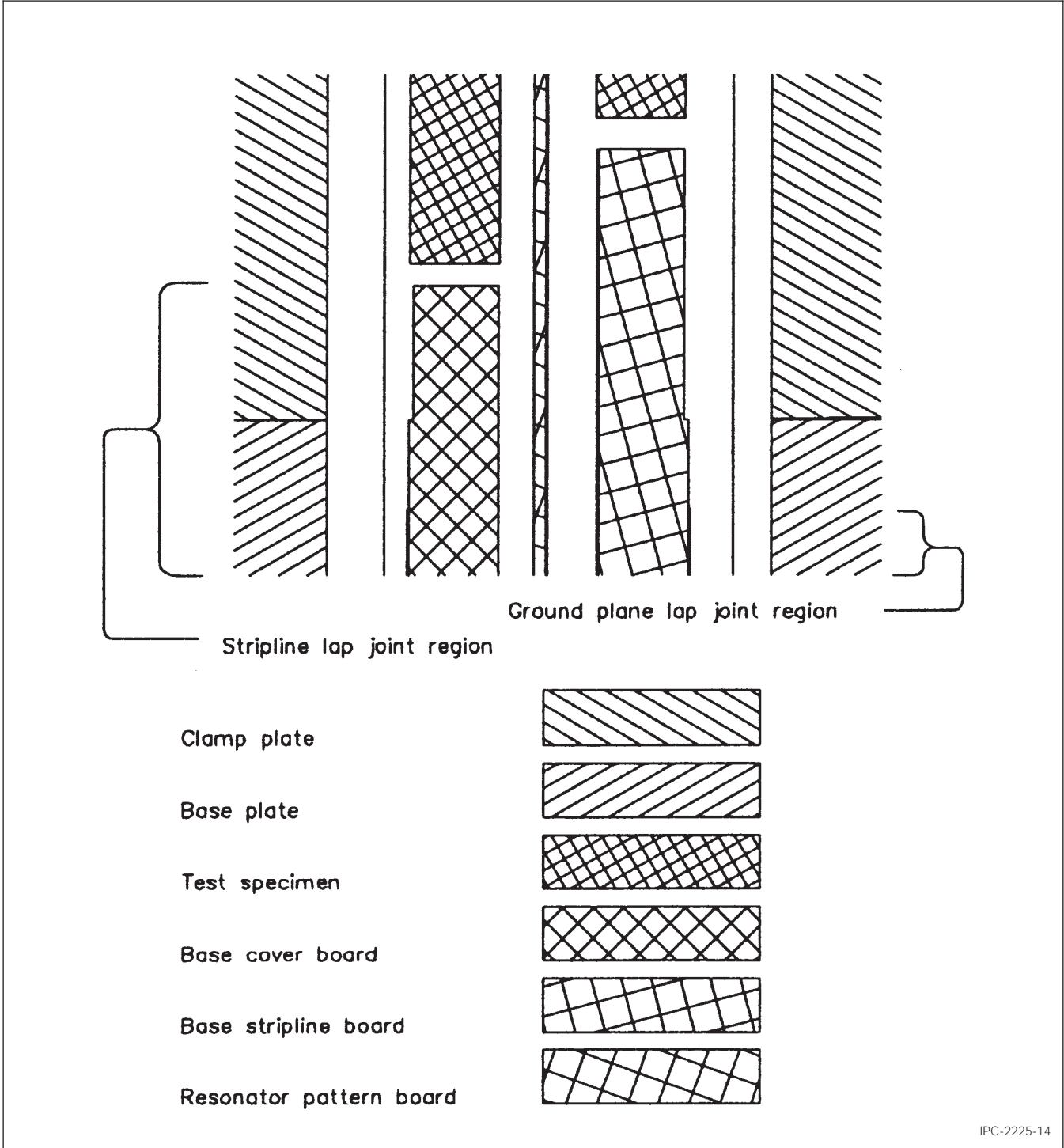| IPC-TM-650		
Number **2.5.5.5**	Subject **Stripline Test for Permittivity and Loss Tangent (Dielectric Constant and Dissipation Factor) at X-Band**	Date **3/98**
Revision **C**		

IPC-2555-10

Figure 10   Slider and Block for Connecting Pressure Block and Base Plate with Allowance for Opening the Fixture

IPC-2555-11

Figure 11   Aluminum Block for Temperature Control and Transfer of Pressure to the Clamp Plates, Fitted with Tapped Holes for Slide, Embedded Steel Ball, and Tapped for Tubing Fittings for Circulating Fluid

Figure 12   Face View of Fixture Assembly

Figure 13   Exploded Side View of Assembly

Stripline lap joint region

Ground plane lap joint region

Clamp plate

Base plate

Test specimen

Base cover board

Base stripline board

Resonator pattern board

IPC-2225-14

Figure 14   Enlarged Exploded Side View Sectioned Through a Probe Line Showing a Lap Conductor Joint

DETAIL A
aluminum
one req'd

Drill 2.06 & countersink for #1 FH screw, 4 places
Drill 3.05 & countersink for #4 FH screw, 4 places
3.05 hole, 2 places

76.76
73.58
72.67
69.49
66.32
50.11

26.64
10.44
7.26
4.09
3.17

1.40
6.35

Dim "A"

22.73
19.56
16.38
10.03
3.68
1.93

17.75
14.58
6.65
3.48

17.75
14.58
6.65
3.48

DETAIL B
aluminum
one req'd

Drill & tap for #1–72 screw, 4 places
Drill & tap for #4–40 screw, 4 places
3.05 hole, 2 places

76.76
73.58
72.67
69.49
66.32
50.11

26.64
10.44
7.26
4.09
3.17

1.40
6.35

Dim "B"

22.73
19.56
16.38
10.03
3.68
1.93

17.75
14.58
6.65
3.48

17.75
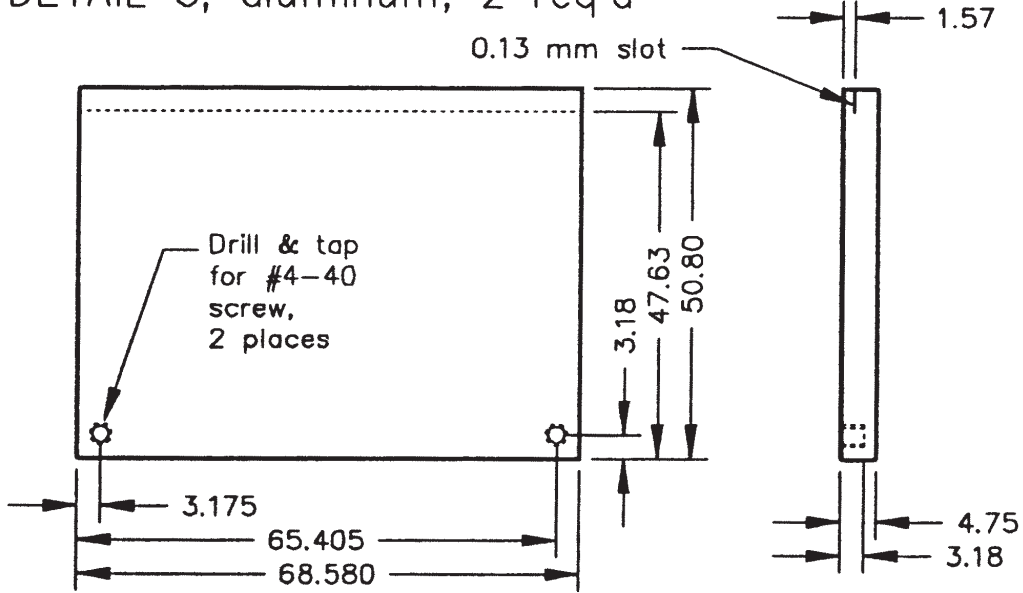14.58
6.65
3.48

Note:
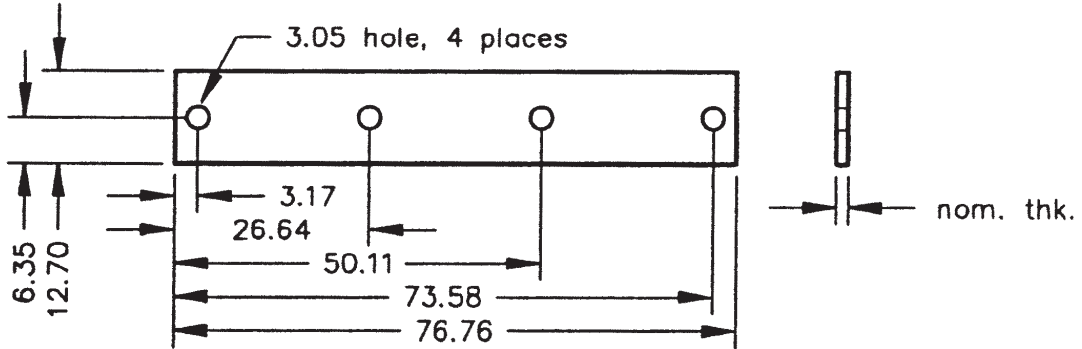|		
Specimen nominal thickness	1.27	1.57
Dimension "A" for base plate 1	4.78	5.08
Dimension "A" for base plate 2	4.47	4.78

IPC-2555-15

Figure 15   Test Fixture Construction, Older Design

DETAIL C, aluminum, 2 req'd

0.13 mm slot

1.57

Drill & tap for #4-40 screw, 2 places

47.63
50.80
3.18

3.175
65.405
68.580

4.75
3.18

DETAIL D, unclad laminate, 2 required

3.05 hole, 4 places

nom. thk.

6.35
12.70

3.17
26.64
50.11
73.58
76.76

IPC-2555-16

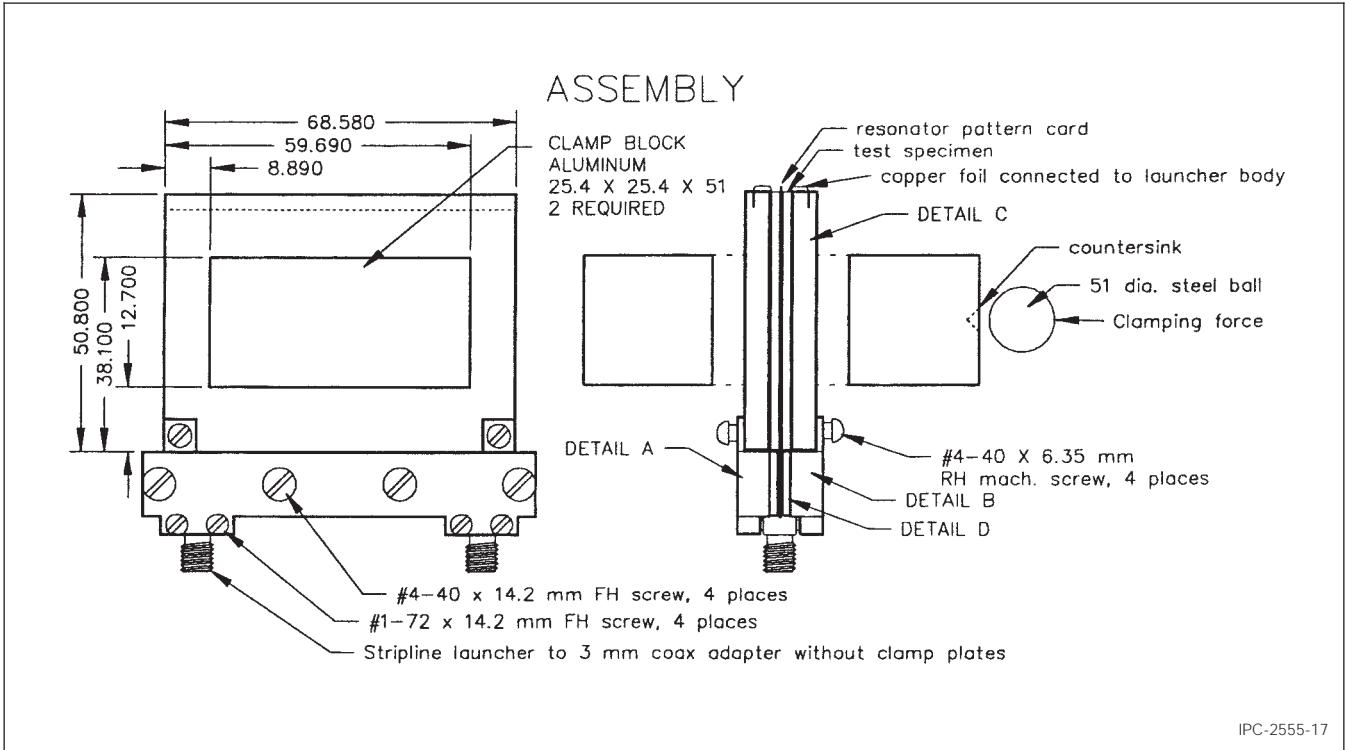**Figure 16   Test Fixture Construction, Older Design (Continued)**

IPC-2555-17

Figure 17   Test Fixture Construction, Older Design (Continued)