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IPC-TM-650 TEST METHODS MANUAL

1 Scope This document describes five methods for determining the amount of signal propagation loss caused by material characteristics of conductors and accompanying structures on printed boards. These losses result in frequency dependent attenuation, α , as described in IPC-2141. Four of these methods to assess this loss are time domain based, and one is frequency domain (FD) based. These methods are:

- Method A: Effective Bandwidth (EBW) method
- Method B: Root Impulse Energy (RIE) method
- Method C: Short Pulse Propagation (SPP) method
- Method D: Single-Ended TDR to Differential Insertion Loss (SET2DIL) method
- Method E: Frequency Domain (FD) method

Method A and B and one aspect of E reduce the attenuation to a single number. Method C and D, and another aspect of E, report the frequency attenuation versus frequency.

Table 1-1 provides an overview of the five methods described in this document for determining the amount of signal propagation loss on printed board conductors.

1.1 EBW (Method A Description) In this method a TDR step with a specified rise time is injected into an unterminated

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Originating Task Group Propagation Loss Test Methods Task Group (D-24b)	

conductor, and the conductor's loss is determined from the degradation of the maximum slew rate of the step rise time at the open end of the interconnect. The maximum slope method described here does not use a 10 - 90% rise time measurements method. Instead, it uses the maximum slew rate to extrapolate an effective bandwidth parameter. The via loss, skin effect loss, and dielectric loss all influence the rise time of the TDR step as it appears at the end of the interconnect. This method is not intended to measure absolute loss or each component of loss. Rather, it determines a relative total loss factor called EBW that can be used to discern loss variations in transmission lines from panel to panel or lot to lot.

1.1.1 EBW Measurement System Caveats This method is not intended for rigorous analysis of the signal attenuation of printed board interconnects but for a simple production test. Therefore, there are several recognized limitations in the measurement methodology:

- This procedure does not deliver absolute values of loss in dB but instead delivers a parameter called EBW which is a qualitative measure of transmission line loss α .
- There is no attempt to separate the various loss components (i.e., skin effect, dielectric, via loss, etc.).

Table 1-1 Methods Overview

	EBW	RIE	SPP	SET2DIL	FD
Instrument	TDR	TDR/VNA	TDT	TDR/TDT	VNA/TDT
Stimulus	Selected for appropriate spectral content	250 ps or specified	11-35 ps	11-35 ps	300 KHz to 10 GHz or as specified
Coupon	>5 cm	1.25 cm and 20.32 cm or as specified	3.0 cm and 10.0 cm	4" (8" effective length)	20.32 cm or as specified
SW	Scope Algorithm	Algorithm and IPC web site pointer	Algorithm and IPC web site for software	Algorithm	Algorithm
Probe	Matched impedance probe	Matched impedance probe	Matched impedance probe, RF connector	High Frequency hand-held probe	Matched impedance probe, RF connector
Test Quantity	Maximum slope in MV/sec	Averaged loss (dB)	$\tan\delta$, ϵ_r , α , β , and Z_0 vs. frequency	SDD21 vs. frequency	Loss fit and slope
Applicability	Printed board fabrication testing	Printed board fabrication testing	Printed board material qualification, printed board model generation	Printed board fabrication qualification and testing	Printed board fabrication testing, printed board design guide specification

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- c) There must be sufficient spectral content within the TDR step pulse for the frequency range of interest where range of interest is determined by application.
- d) The repeatability of the measurement is limited by the noise and jitter response from the TDR instrument.

1.1.2 EBW Test Coupon and Conductor Caveats This method is designed to be used on any conductor. However comparison between measurements is only valid for like inter-connect structures.

The launch vias should be designed with minimum return loss. It is recommended that the test coupon or conductor be of a length greater than 5.0 cm [2.0 in].

EBW applicable documents include IPC-2141, IPC-TM-650, Method 1.9 and Method 2.5.5.7.

1.2 RIE (Method B Description) In this method a TDR step with a specified rise time is injected into each of two lengths of an unterminated conductor. The gated derivative of the reflected edges is an impulse response for each respective line. The RIE value is the ratio of energy obtained by integrating the impulse responses. One of the two lengths is intended to be a relatively short piece; the other is substantially longer and in close proximity to a considerably long conductor on the same printed board layer. The RIE ratio is a single value that is directly proportional to the aggregate transmission line loss α , which is described in IPC-2141.

1.2.1 RIE Measurement System Limitations RIE values can vary depending on equipment used and how the tests were performed. Following the specified method ensures consistent results. Both single-ended and differential line measurements have limitations in common which include the following:

- a) RIE values are dependent on equipment bandwidth; this document specifies only a minimum requirement for the TDR signal source.
- b) When attempting correlation between different systems, it is critical that all systems have the same bandwidth.
- c) The probe cabling, launch, test coupon vias affect measurement accuracy.
- d) All RIE loss values are derived and not directly measured.
- e) The RIE process utilizes a filter algorithm to improve measurement consistency.

1.2.2 RIE Test Coupon and Conductor Caveats Various limitations can be attributed to test samples and probing such as:

- a) The probe and launch structure reduces the signal energy injected into the transmission line.
- b) Crosstalk and associated effects, other than differential coupling, are out of the scope of the RIE method.
- c) The RIE method applies to reference structures and test structures with specified transmission line lengths.

RIE applicable documents include IPC-2141, IPC-TM-650, Methods 1.9 and 2.5.5.7.

1.3 SPP (Method C Description) The SPP method allows the extraction of broadband printed board electrical characteristics that affect signal propagation using Time Domain Reflectometry/Time Domain Transmission (TDR/TDT) equipment. The SPP method produces frequency dependent measurement results. Such frequency-dependent parameters include the propagation constant (attenuation and phase constant), dielectric constant, loss tangent, and characteristic impedance. Conductor resistivity and line capacitance are also assessed. The extracted parameters may be used to generate predictive causal transmission line models for system performance evaluations as well for monitoring production line output.

The SPP technique employs a time-domain measurement that is used to extract the broadband permittivity. The technique is used on representative stripline structures built with small interface discontinuities such as lands and vias.

A short pulse is injected into two lines of different lengths. Signal processing of the digitized pulses consists of rectangular time windowing of the unwanted reflections from interface discontinuities. This is followed by Fourier transformation. From the ratio of the two Fourier transforms, the total attenuation $\alpha(f)$ and phase constant $\beta(f)$ are obtained. $R(f)$, $L(f)$, $C(f)$, and $G(f)$, namely resistance, inductance, capacitance, and conductance per unit length, are calculated using a causally-enforced two-dimensional (2D) field solver that has a built-in Debye function for the relation between $C(f)$, and $G(f)$, which enforces the Kramer-Kronig causality requirement. The total attenuation $\alpha(f)$ and $\beta(f)$ are fitted to the measured values and smooth interpolation and extrapolation is made over the desired frequency range. The broadband $Z_0(f)$ can also be obtained from Equation [1-1]:

$$Z_0(f) = \frac{\Gamma(f)}{G(f) + j2\pi C(f)} \quad [1-1]$$

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The transmission line parameters $R(f)$, $L(f)$, $C(f)$, and $G(f)$ are a consequence of determining $\alpha(f)$ and $\beta(f)$ from the fitted transmission line solution to the measurements. The final step is the extraction of the relative dielectric constant ϵ_r and loss tangent, $\tan\delta$.

Measurements made of the capacitance and loss tangent of an additional large parallel plate structure embedded in the same layer with the signal conductor allows the extraction of ϵ_r and $\tan\delta$ at very low frequencies. The final $R(f)$, $L(f)$, $C(f)$, and $G(f)$ are used to extract the complex permittivity using Equations [1-2] and [1-3].

$$\epsilon_r(\omega) = \left(\frac{C(\omega)}{C_{1MHz}} \right) \times \epsilon_{r1MHz} \quad [1-2]$$

$$\tan\delta(\omega) = \frac{G(\omega)}{\omega C(\omega)} \quad [1-3]$$

where C_{1MHz} is the calculated line capacitance at a low frequency such as 1 MHz and ϵ_{r1MHz} is the value obtained at 1 MHz from the parallel plate measurement. ω is the angular frequency and equal to $2\pi f$.

The IPC SPP method is intended for printed boards, however it can be extended to measure coaxial single-ended and differential cables, flex cables, multi-chip module ceramic wiring, single and multi-chip organic module wiring, thin-film wiring, and on-chip wiring. The extraction results produce results in frequency range between 10 KHz to 40 GHz, depending on the quality of the TDR equipments and test coupon structure.

1.4 SET2DIL (Method D Description) In this method a TDR step is injected into one half of a 101.6 mm [4.0 in] differential pair, which has the two legs of the differential pair shorted together at the far end. The waveforms of both halves of the differential pair are captured and manipulated to derive SDD21 (and Z_0 , if desired) of the equivalent differential pair.

1.4.1 SET2DIL Measurement System Caveats SET2DIL produces the SDD21 value for the differential pair being measured; it is not intended to rigorously differentiate between loss elements (conductor vs. dielectric, for instance). The same structure can also be used to measure the differential impedance, though that calculation isn't covered in this specification. Some other limitations of SET2DIL include:

- a) SET2DIL SDD21 measurements will include losses due to the vias, for stripline traces. To minimize errors induced by vias, the following limitations are made to the SET2DIL coupon design:
 - i. The coupon has an effective length of 203.2 [8.0 in], which will cause the trace losses to overwhelm small via losses.
 - ii. Stripline traces on the bottom portion of the board (lower layers) are measured from the top to minimize via stub effects. Upper stripline layers are measured from the bottom of the board.

- b) SET2DIL SDD21 measurements will include an error term from SDD11 effects if the differential trace being measured isn't 100 Ω (2x the reference impedance of 50 Ω).

- i. The coupon has an effective length of 203.2 mm [8.0 in], causing the trace insertion losses (SDD21) to overwhelm the relatively small return loss.
- ii. The primary purpose of SET2DIL is to ensure the trace properties match that of those in simulations. Thus, SDD21 from simulations with a 50 Ω reference can be used as the measurement criteria for SET2DIL, making the reference error difference moot.

1.5 FD (Method E Description) Three of the previously described methods use TDR to determine the loss characteristics of a printed board. This approach utilizes a Vector Network Analyzer (VNA) or the fast fourier transform (FFT) of a TDT for this purpose. The result is a direct measure of frequency domain attenuation and loss. VNA equipment includes calibration to the launch pad which must be used. The insertion loss is directly related to transmission line design parameters utilized in signaling design analysis. The metric for the FD method is the slope of the RMS insertion loss fit for a specified frequency range.

2 APPLICABLE DOCUMENTS

IPC-2141 Controlled Impedance Circuit Boards and High Speed Logic Design

IPC-TM-650 Test Methods Manual

- 1.9 Measurement Precision Estimation for Variables Data
- 2.5.5.7 Characteristic Impedance of Lines on Printed Boards by TDR

IEEE802.3ap Std 2007 Annex 69b.4.1, "Fitted attenuation"

2.1 Technical Publications

R. Mellitz, T. Ballou, and S.G. Pytel, "Energy Based TDR Loss Method for PB Manufacturers," from IPCWorks 2005, Las Vegas, NV.

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B. Gore, J. Loyer, R. Mellitz, M. Gaudion, J. Burnikell, P. Carre, "Towards a PB Production Floor Metric for Go/No Go Testing of Lossy High Speed Transmission Lines," from IPC Expo 2008.

A. Deutsch, G. Arjavalingham, and G. Kopcsay, "Characterization of Resistive Transmission Lines by Short Pulse Propagation," in IEEE Microwave and Guided Wave Letters, vol. 2, no.1, January 1992.

A. Deutsch, G. Arjavalingham, G. Kopcsay, and M. Degerstrom, "Short-Pulse Propagation Technique for Characterizing Resistive Package Interconnections," in IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol. 15, no. 6, December 1992.

A. Deutsch, T. M. Winkel, G. Kopcsay, C. Surovic, B. Rubin, G. Katopis, B. Chamberlin, R. Krabbenhoft, "Extraction of $\epsilon_r(f)$ and $\tan\delta(f)$ for Printed Circuit Board Insulators Up to 30 GHz Using the Short Pulse Propagation Technique" in IEEE Transactions on Advanced Packaging, vol. 20, no. 1, February 2005.

A. Deutsch, C. W. Surovic, R. S. Krabbenhoft, G. V. Kopcsay, B. J. Chamberlin, "Prediction of Losses Caused by Roughness of Metallization in Printed-Circuit Boards," IEEE Transactions on Advanced Packaging, vol. 30, no.2, pp.279-287, May 2007.

A. Deutsch, Roger Krabbenhoft, C. W. Surovic, B. Rubin, T-M. Winkel, "Use of the SPP Technique to Account for Inhomogeneities in Differential Printed-Circuit-Board Wiring" Digest of SPI'08, Signal Propagation on Interconnects, May 12-15, Avignon, France, 2008 pp. 12-16.

G. Arjavalingham, A. Deutsch, G. V. Kopcsay, J. K. Tam, "Methods for the Measurement of the Frequency Dependent Complex Propagation Matrix, Impedance Matrix, and Admittance Matrix of Coupled Transmission Lines," U.S. Patent, patent 5,502,392, March 26, 1996.

J. Loyer, R. Kunze, "SET2DIL: Method to Derive Differential Insertion Loss from Single-Ended TDR/TDT Measurements," DesignCon 2010.

3 Test Coupons (Specimens)

3.1 Common Characteristics The coupons for all the methods contain transmission lines. The SPP coupon also includes a small disc structure. The following are general guidelines for designing transmission line test structures for test methods within this document. These transmission line test structures or interconnects may be placed within the

functional area of the printed board or within test coupons. A coupon is a section of the printed board that is designated for test structures and is removed from the panel after printed board fabrication is completed. Differences between the characteristics of test and functional interconnects may exist. The relative merit of test structure placement relation to functional circuit is beyond the scope of this document.

3.1.1 General Nomenclature – Coupons It is recommended that coupons have labels that contain information about the associated test line signal layer; for example, L1, S3, etc. Labeling of the contact land for differential conductors **shall** clearly indicate the matched pair.

It is recommended that test coupons include a printed board serial number, part number, and date code.

3.1.2 Ground and Reference Planes All reference planes in the coupon **shall** be connected together within the coupon area and be independent of those planes in the functional circuit area. Ground and reference plane dispensation within the functional area is beyond the scope of this document.

3.1.3 Differential Coupons The differential line is also known as a balanced transmission line. The probing area should contain four contact lands: one contact land for each of the two signal conductors in the differential pair and two contact lands connected to the reference plane(s).

3.1.4 Probe Launch The probe launch is comprised of a PTH or other via structure and ground contact rectangular pad and an example is depicted in Figure 3-1. The hole diameter is recommended to be the smallest hole that is appropriate for the respective technology. Some printed boards may employ blind and buried vias. The recommended pitch between ground and signal pad for high volume testing is 1.016 mm [0.040 in] or 2.54 mm [0.100 in]. Higher accuracy can be achieved with smaller ground pad to signal pad spacing and use of multiple ground vias.

3.1.5 Connector Launch A high bandwidth connector launch may be used instead of probe launch as show in Figure 3-2.

Figure 3-3 provides an example of high bandwidth connector launch.

3.1.6 General Surface Condition The panel test coupons **shall** have the same surface plating and use the same solder mask requirements as the functional printed board.

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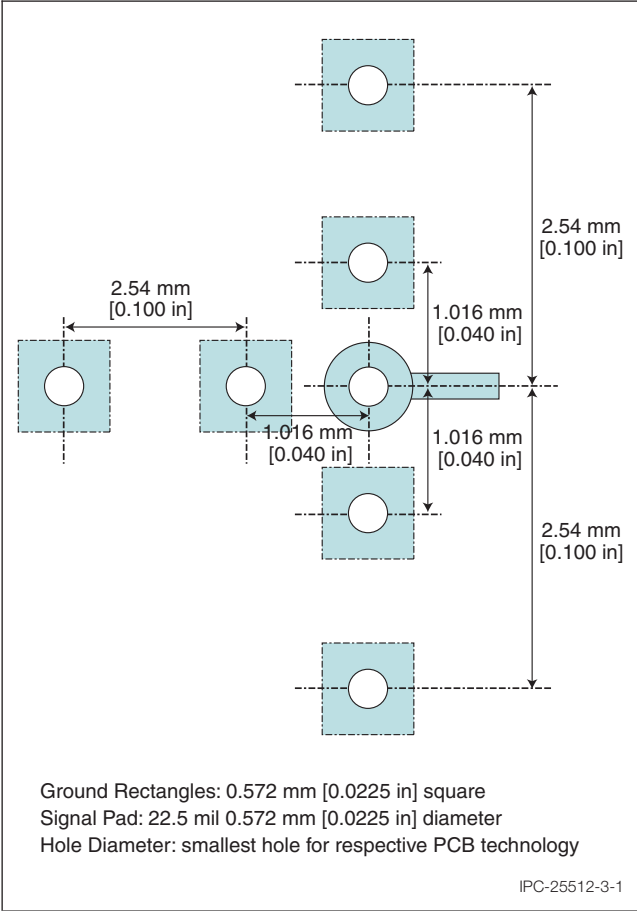


Figure 3-1 Example of Probe Launches

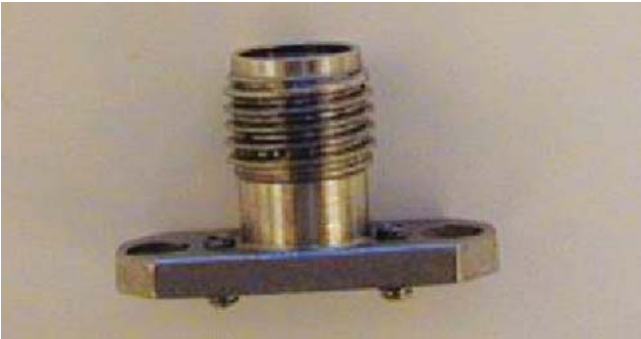


Figure 3-2 High Bandwidth SMA Connector Example

3.1.7 General Thieving Thieving which is the use of nonterminated copper structures, such as planes, pads, and/or conductors adjacent to test lines that ensure plating consistency may be used on test coupon. All thieving structures, if used, **shall** be placed at least six times the width of

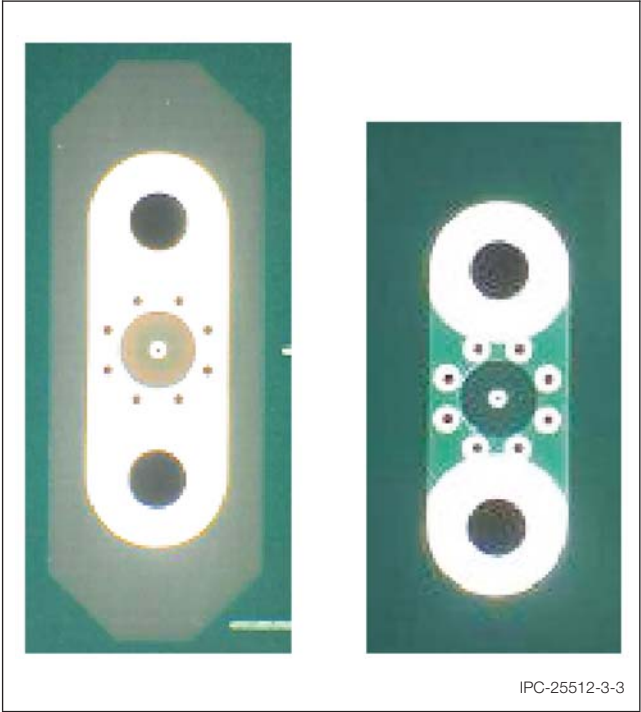


Figure 3-3 High Bandwidth Connector Launch Example

the signal conductor (of the test interconnect) or 2.5 mm [0.100 in], whichever is greater, from each test interconnect.

3.1.8 Termination Types of Test Lines There are two types of line styles that may be used. The first is terminated on each end with a launch. These lines are the only type that are employed with the SPP and VNA method. The second type of line is terminated on one end with a launch while the other end is just the end of a conductor e.g., unterminated. The EBW and RIE method may use either terminated or unterminated lines types. The SET2DIL structure requires no termination.

3.1.9 Test Line Routing The test lines **shall** be routed over/under contiguous ground/voltage planes. The test line conductors **shall** be kept at least six times the height of the laminate layer thickness which is closest to the conductor or 2.54 mm [0.100 in], whichever is greater; from printed board structures include voids, plane splits, other conductors, and holes.

It is recommended that test lines be straight.

3.1.10 Environmental Conditioning: Temperature and Humidity Temperature and humidity effect loss measurements. Consistent results can be obtained by storing test

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specimens at 23 °C (± 2 °C) [73.4 °F (± 3.6 °F)] and 40% RH (± 5% RH) for no less than 48 hours.

3.1.11 Fiberweave It is recommended that the test conductors route at an angle 10 degrees to glass cloth weave.

3.2 Probing If probing is performed manually, operators are urged to monitor the oscilloscope trace to ensure proper connectivity. In the case of SMA connectors that are slip-fit, it must be ensured that the amplitude of the detected pulse is unchanged even when a small additional force is applied to the holding stage movement (within the tolerance of the set-up) for accurate, repeatable results. In the case of coaxial probes, a small increase of the z-micropositioner travel (within the tolerance of the probe allowed force) should also not change the shape of the pulse. Automated probing can improve the contact reliability.

For the most part the FD measurements do not use TDR probes. They employ either connector or microprobes that have respective calibration kits.

3.3 Test Coupon Characteristics

3.3.1 Test Line Impedance It is recommended to use lines that are 50 Ω single ended or 100 Ω differential for SPP. Using other impedance lines are permitted but the applicability is the responsibility of the user. EBW, RIE, SET2DIL, and FD methods can use other impedances. It is recommended to limit the line characteristic impedance Z_0 nonuniformity as measured in TDR to not exceed 20% peak-to-peak along the length of the lines. The difference in impedance between the two lines used for SPP and RIE measurement **shall not** exceed 5%.

3.3.2 EBW Test Lines Test lines for EBW **shall** be greater than 5.08 cm [2.00 in] in length. Longer test interconnects occupy more printed board or panel area. For short interconnects, the relative impact of via loss to other loss effects may be disproportionately large.

3.3.3 RIE Test Lines The RIE test sample **shall** contain one transmission (or interconnect) test structure and one reference transmission line per layer. The Reference is recommended to be 2.54 cm [1.00 in]. The test line **shall** be between 15.24 cm [6.00 in] and 30.49 cm [12.0 in]. The specific length **shall** be specified by printed board customers or vendors. If fold back is required for striplines because of limited printed board area, maintain maximum spacing of 0.254 cm [0.10 in] between loop back trace legs. Foldbacks are not recommended for microstrip structures.

3.3.4 SPP Test Structures SPP test structures **shall** have the following attributes:

- Conductors of varying lengths
- Signal – Ground launch/capture structures
- Disc structures to be used for low frequency capacitance measurements

3.3.4.1 SPP Test Lines The goal is to compare the captured waveforms from two conductors which are as identical in cross section and laminate building blocks as the manufacturing process allows.

The SPP technique relies on the extraction of waveforms from two different conductor lengths. The specific conductor lengths used are dependent on the application.

The ratio of the lengths of the long and short conductors **shall** at least be three to one. The following are recommended:

- 3.0 cm [1.181 in] and 10.0 cm [3.937 in] conductor combination. This combination provides the best output, but it can be slightly more difficult to find conductors which are well matched in their physical structure.
- 2.0 cm [0.787 in] and 8.0 cm [3.149 in] conductor combination. This combination is useful in thin cards (<0.10 cm [0.04 in]) for extended high-frequency range when using coaxial probes for contact.
- 5.0 cm [1.969 in] and 15.24 cm [6.00 in] conductor combination. This combination is suited for production floor test coupons.

Printed boards over 0.254 cm [0.1 in] thick **shall** use microvias, back-drilling, top milling or blind vias in order to reduce the end discontinuities.

3.3.4.2 SSP Disc Structure A 12.7 mm [0.5 in] diameter disc is included in the signal layer artwork. The 1 MHz capacitance of this disc is assessed using an LCR meter. The disc capacitance is assessed through adjacent PTHs, one of which is attached to the disc by a short conductor; the other is attached to the reference planes. In the event that both planes are not at the same reference potential, an isolation border is placed around the disc structure to prevent shorting two different reference levels.

A “dummy” PTH/conductor structure which is of the same design as the PTH/conductor used to access the disk is also included. The capacitance of this dummy structure is subtracted from the capacitance of the disc structure.

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The layout of the disc structure is shown in Figure 3-4. The red text is on the external surface for pad identification purposes. In a multi-signal layer cross section, disks can be “stacked” vertically to facilitate later cross-sectioning if desired (e.g., the disc for layer 6 is directly under the disc for layer 3). The voltage planes around each disc are connected together at the reference PTH and isolated from the rest of the test vehicle through the use of a voltage divider.

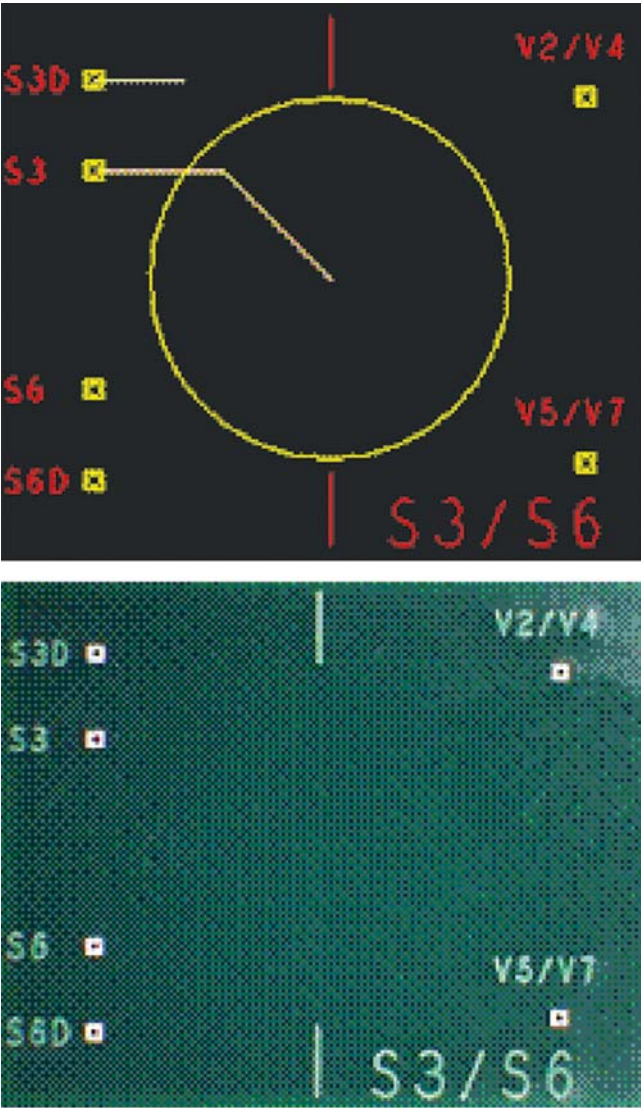


Figure 3-4 SPP Disc Structure

3.3.4.3 SPP Test Coupon Design An example is shown of a typical coupon layout with 3 cm and 10 cm [1.18 in and 3.94 in] long lines and the 12.7 mm [0.5 in] disc in Figure 3-5.

The contacts are shown using the SMA connectors described in Figure 3-3. This is a minimum configuration. Additional lines would need to be added for differential line testing. The layout in Figure 3-5 requires 2.0 cm x 16 cm [0.8 in x 6.3 in] of card space.

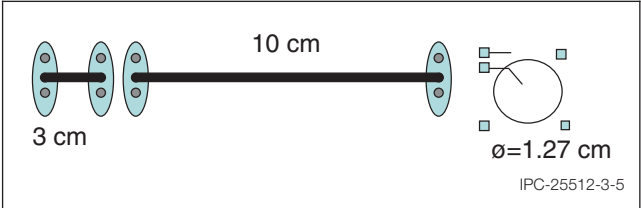


Figure 3-5 Example of Test Coupon for Single Line Case

3.3.5 SET2DIL Test Lines The SET2DIL test coupons **shall** contain one DUT (Device Under Test) for each impedance/layer combination being controlled, and a “thru” reference structure.

3.3.6 FD Test Lines The FD test sample shall contain one transmission (or interconnect) test line per layer. The reference line shall be between 1.27 cm [0.5 in] and 2.54 cm [1 in]. The test line **shall** be between 15.24 cm [6 in] and 30.49 cm [12 in]. The recommended line is 1.27 cm [0.5 in] for the reference line and 20.32 cm [8 in] for the test line. The specific length **shall** be specified by printed board customers or vendors.

3.3.7 Surface Finish No matter what surface finish is used, one should ensure the surface of the launch/capture structure is clean and that the contact of the probes is not affected by residues and/or oxides. OSP (organic solderability preservative) finishes may inhibit probing of fine-pitched probes and may need to be removed from the probe area.

In the lab based qualification/verification assessment, one can facilitate this by slight burnishing (a pencil eraser often works well), followed by cleaning with isopropyl alcohol (IPA).

In production floor assessments, the probe design should be designed to break through any potential oxides or contaminants.

4 Apparatus

4.1 Differential and Single Ended Measurements Both single ended and differential measurement can be applied to all the test methods. The measurement process for a differential measurement is identical to that of a single ended test. For

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the RIE, SPP, and EBW methods the differential voltage measurement is used where the single ended measurement is specified. For SET2DIL, a slightly different algorithm is used for single-ended (S21) vs. differential (SDD21) signals. For the FD (VNA) method, SDD21 is used in place of S21.

4.1.1 TDR Differential Channel Synchronization The two excitation channels need to be synchronized and have the same amplitude. One recommended method is to use an oscilloscope that has timing adjustments both in the TDR heads and in the detector heads. Such a setup is performed on a short pair of lines or zero-delay configuration. The steps are as follows:

- 1) Channel 1 on the source side is propagated and detected by Channel 3 on the detect side. The pulse or step is recorded and displayed on the screen. Next, Channel 2 on the source side is propagated to Channel 3 on the detect side. The new pulse or step is overlapped with the one on the screen. If there is a difference, the differential TDR skew is adjusted until they are coincident. This makes sure that the two sources do not have any difference in time, as illustrated in Figure 4-1.

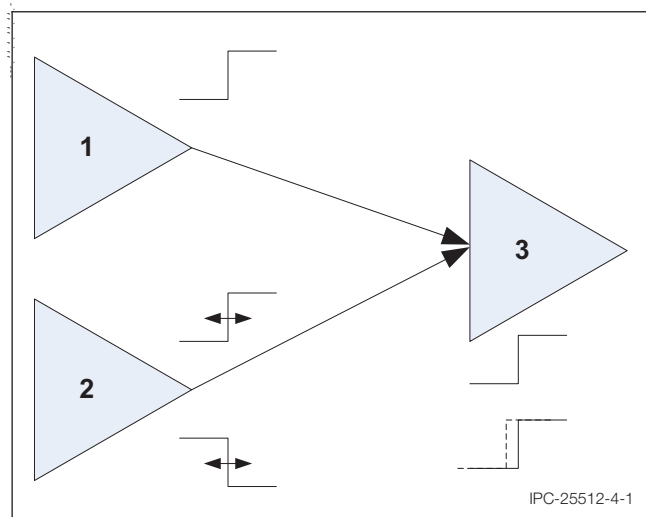


Figure 4-1 TDR Pulse Synchronization for Differential Application

- 2) Next, the detector channels are adjusted. Channel 1 on the source side is propagated and detected at this time by Channel 4 on the detect side. This is compared to the pulse or step obtained by the path of 1 going into 3. If they are not synchronized, the Horizontal Skew Adjustment is used to bring the timings together. Similarly, Channel 3 (or

4) is used as a source into channels 1 & 2; channel 2's horizontal skew is adjusted to bring the timings together, see Figure 4-2. If there is any amplitude difference due to detector amplification difference, the Channel 4 (or 2) attenuation can be adjusted to match the waveform of Channel 3 (or 1).

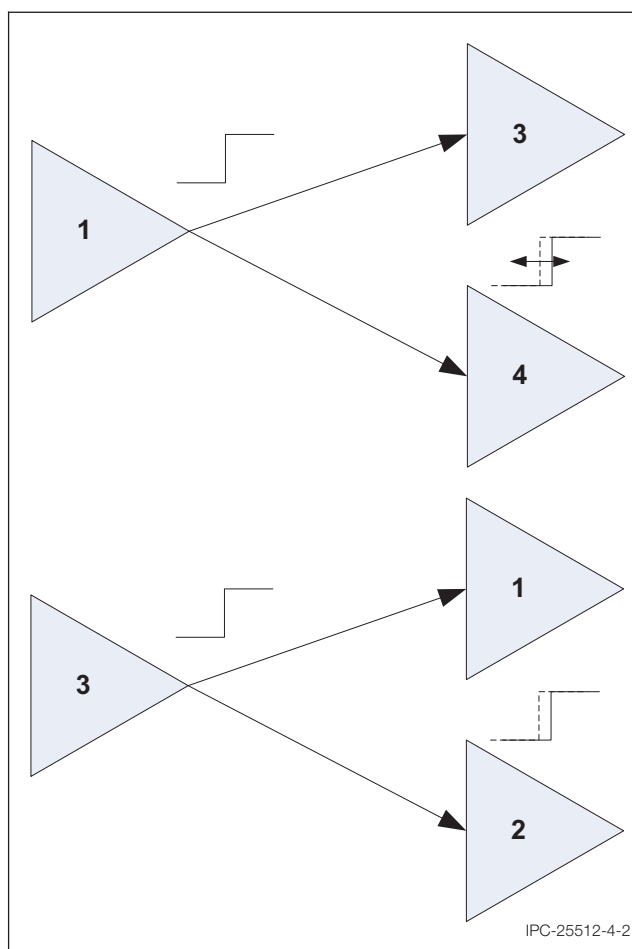


Figure 4-2 TDR Receiver Horizontal Skew Adjustment

Both setup steps are needed for TDT and SPP; the first step alone is enough for TDR used in RIE and EBW; and only step 2 is required for SET2DIL. Step 1 is repeated for Odd-Mode and for Even-Mode measurements in the differential case.

Note: Channel 2's excitation must be in the same mode that will be used during measurements (even or odd) during synchronization; the pulse timing may vary, depending on the excitation mode. Using a math function to invert the waveform at the receiver might be necessary for odd mode excitation.