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IPC-TM-650
TEST METHODS MANUAL

Number	
2.5.5.12	
Subject	
Test Methods to Determine the Amount of Signal Loss on Printed Boards	
Date	Revision
07/12	**A**
Originating Task Group	
Propagation Loss Test Methods Task Group (D-24b)	

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 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:

a) 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.

b) 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)	Tanδ, 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

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 interconnect 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]:

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

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].

$$\varepsilon_r(\omega) = \left(\frac{C(\omega)}{C_{1MHz}}\right) \times \varepsilon_{r1MHz} \qquad [1\text{-}2]$$

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

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.

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. Arjavalingam, 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. Arjavalingam, 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 $\varepsilon_r(f)$ 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. Arjavalingam, 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.

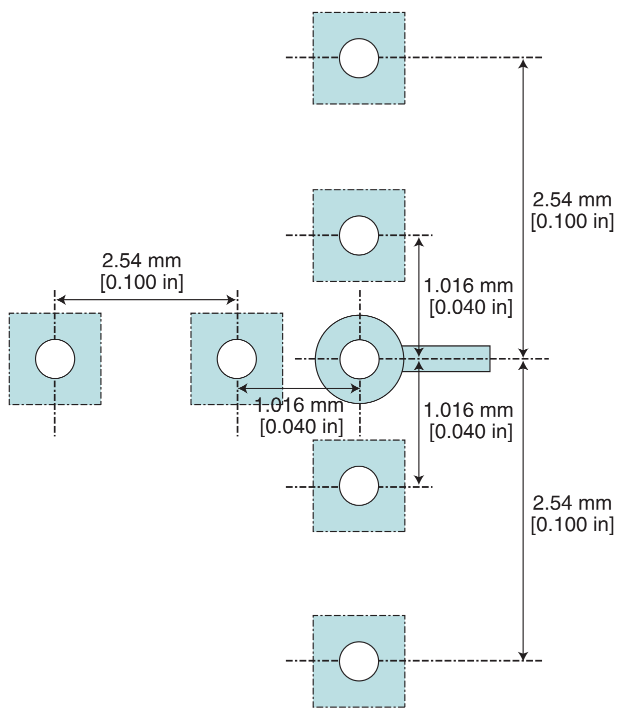
3.1.3 Differential Coupons The differential line is also known as a balanced transmission line. The probing area should contain four contact lands: one contact land for each of the two signal conductors in the differential pair and two contact lands connected to the reference plane(s).

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.



Ground Rectangles: 0.572 mm [0.0225 in] square
Signal Pad: 22.5 mil 0.572 mm [0.0225 in] diameter
Hole Diameter: smallest hole for respective PCB technology

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Figure 3-1 Example of Probe Launches

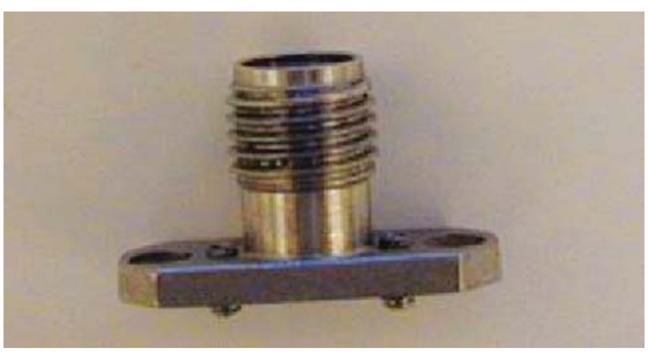

Figure 3-2 High Bandwidth SMA Connector Example

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

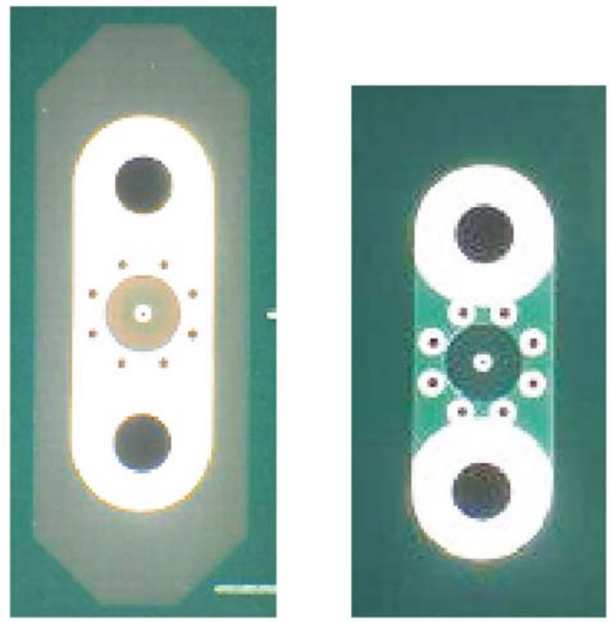

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Figure 3-3 High Bandwidth Connector Launch Example

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 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 or 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 disproportionably 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:

a) 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.

b) 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.

c) 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.

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.

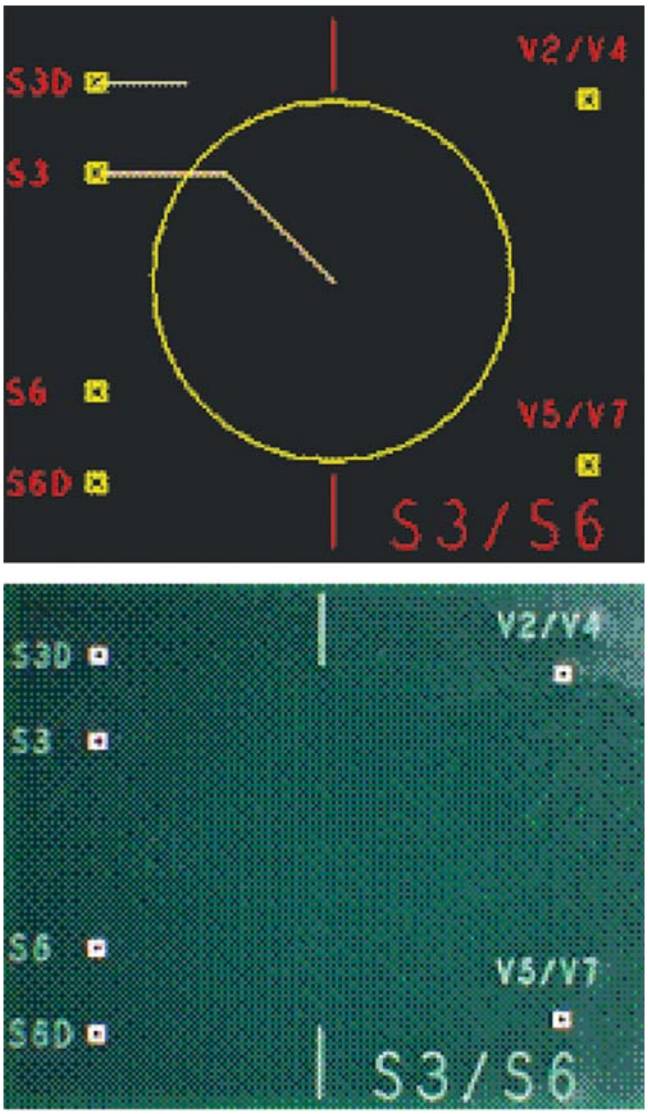


Figure 3-4 SPP Disc Structure

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.

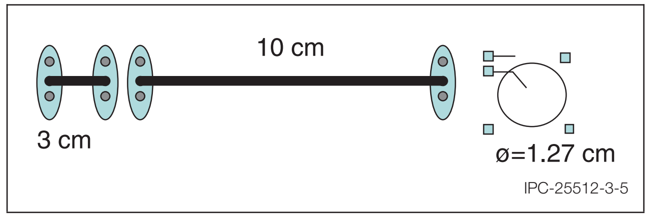


Figure 3-5 Example of Test Coupon for Single Line Case

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 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.

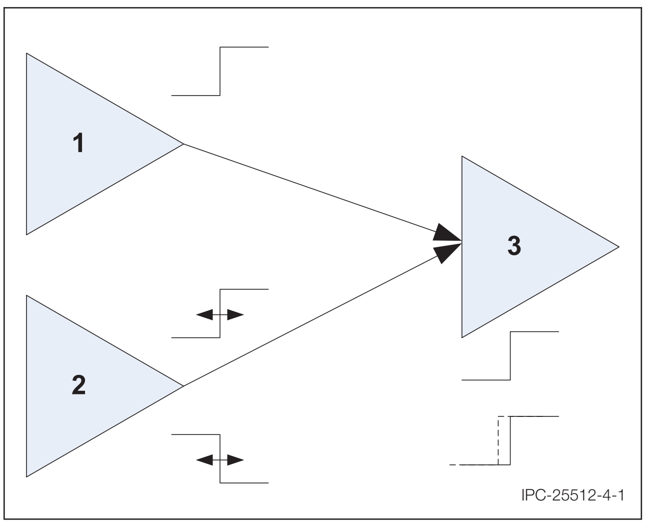


Figure 4-1 TDR Pulse Synchronization for Differential Application

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).

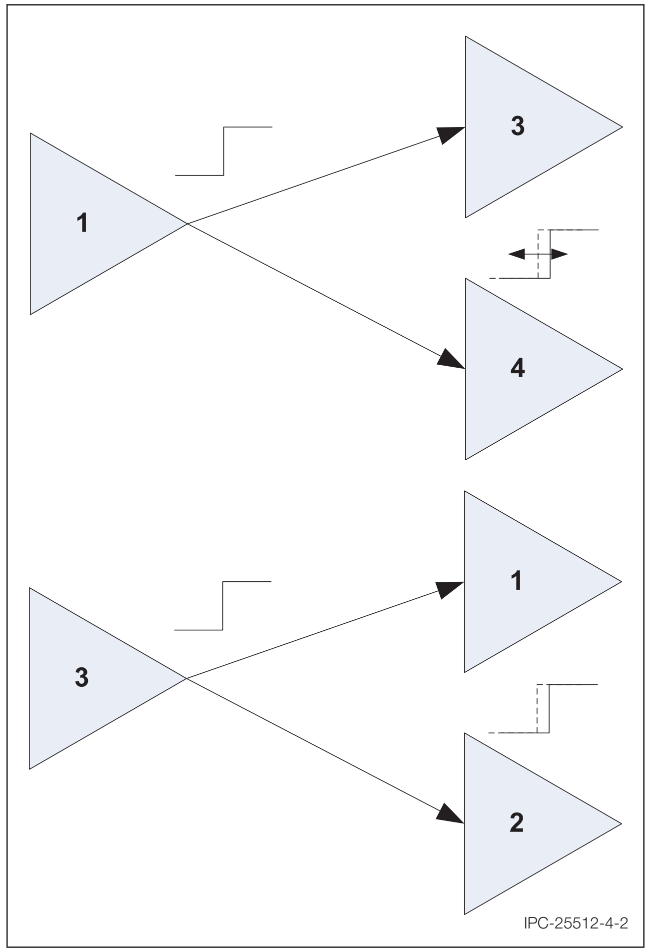


Figure 4-2 TDR Receiver Horizontal Skew Adjustment

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.

Note: Equipment drift may occur as a function of time and environment; check with equipment manufacturer for proper calibration frequency.

4.2 EBW, RIE, and SET2DIL Apparatus EBW, RIE, and SET2DIL utilize a TDR measurement system which **shall** be composed of a step generator, high-speed sampling oscilloscope, and all the necessary accessories for connecting the TDR unit to the test specimen depicted in Figure 4-3. IPC-2141 provides a short discussion of the TDR system architecture, system considerations, and the TDR measurement process.

4.3 SPP Apparatus SPP utilizes a TDR measurement system with the addition of one more sampling output head and impulse forming networks placed between the TDR Sample head and on probe. This type of setup comprises a TDT system as shown in Figure 4-4.

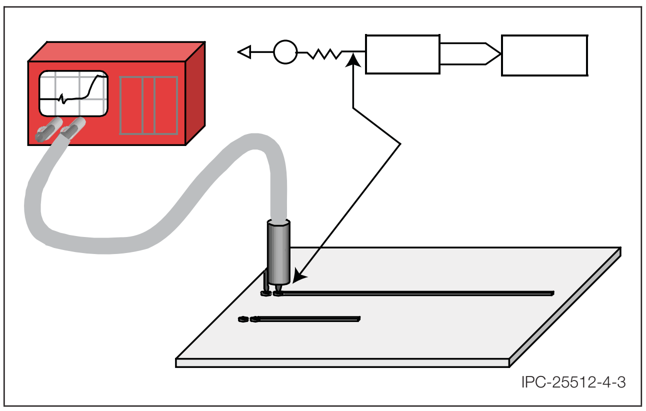


Figure 4-3 TDR Measurement Components

Three general probing solutions may be used. These include: microprobes, SMA connectors, and handheld probes. Each of these methods embodies a test structure(s) in near proximity and on the same printed board layer.

4.4 Measurement System Requirements

4.4.1 System Calibration Follow the TDR instrument manufacturer's recommendation for the frequency of factory calibration. TDR system ''field'' checks are to be performed at regular intervals to ensure proper operation of the test systembetween the less regular factory calibrations. Field checks are required for the following reasons:

a) TDR instrument specifications vary with temperature.

b) TDR instrument specifications vary with time (drift).

c) TDR instrument specifications vary due to minor ESD damage.

d) TDR instrument factory calibration may not include auxiliary components (e.g., cables, probes, etc.).

TDR system field checks should also be performed after a change of any system component (such as, cable, probes, etc.). Ensure that the TDR instrument has been operating for at least 30 minutes prior to any field check or test measurement procedure. Use proper ESD control methods to avoid damage to the TDR instrument in all field check and test

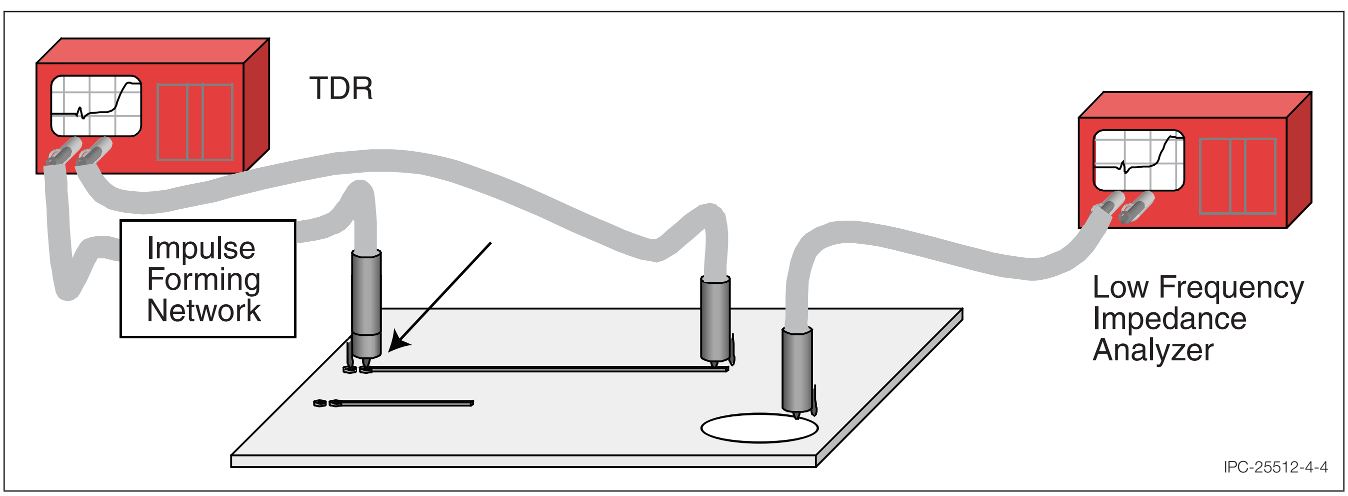


Figure 4-4 SPP TDT/IFF Measurement Components

measurement procedures. ESD control components can include static dissipative mats, deionizer systems, and operator gowning.

4.4.2 Premeasurement Checks The test measurement should be performed after the completion of the field check process. Ensure that the plane of the signal line of a microstrip (or embedded microstrip) structure is at least a distance equal to six times the width of the microstrip signal line from any material (such as the testing table) that can affect the dielectric environment of the microstrip line. If the tests are being conducted with hand probe(s), care must be taken to ensure that the hands and/or arms of the operator do not contact any surface of the printed board over the transmission line being tested. Probes should be applied to the test points with sufficient force to ensure proper electrical contact between the conductor and the probe assembly. Consistent application (that is, force, angle of placement, etc.) of the probes onto the test points is important to ensure repeatable measurement results. Before recording any measurement results, ensure that the TDR waveform is stable (that is, not drifting in amplitude or time) otherwise measurement error will occur. Ensure that the temperature and humidity of the test environment are within TDR instrument specifications and are stable.

4.4.3 Method for Evaluation of Measurement Repeatability Measurement repeatability is described in IPC-TM-650, Method 1.9. This method also describes a process to evaluate the reproducibility of a measurement system for multiple operators, on different days, and when using different instruments. This evaluation process should be followed and a precision-to-tolerance ratio acceptable to the customer obtained.

4.4.4 TDR Requirements In general, the following describes minimum TDR requirements. Improvement to these requires agreement between customer and vendor.

4.4.4.1 EBW: TDR Requirements The voltage measurement resolution of the TDR unit **shall** be at least 1% of the step amplitude. Step aberrations should be ± 3% or less over the zone 10 ns to 20 ps before step transition; +10%, -5% or less for the first 300 ps following step transition; ±3% or less over the zone 300 ps to 5 ns following step transition; ± 1% or less over the zone 5 ns to 100 ns following step transition; 0.5% after 100 ns following step transition. The time base accuracy **shall** be less than 2 ps.

4.4.4.2 RIE: TDR Requirements The voltage measurement resolution of the TDR unit shall be within 1% of the step amplitude. Step aberrations should be ± 3% or less over the zone 10 ns to 20 ps before step transition; +10%, -5% or less for the first 300 ps following step transition; ± 3% or less over the zone 300 ps to 5 ns following step transition; ± 1% or less over the zone 5 ns to 100 ns following step transition; 0.5% after 100 ns following step transition. The time base accuracy **shall** be less than ± 1% of full scaled used. The captured time **shall** be at least twice the transit time and shall contain at least 2000 samples. The time between samples **shall** also be less than 25 ps.

4.4.4.3 SPP: TDR Requirements The voltage measurement resolution of the TDR unit **shall** be at least 1% of the step amplitude. Step aberrations should be ± 3% or less over the zone 10 ns to 20 ps before step transition; +10%, -5% or less for the first 300 ps following step transition; ± 3% or less over the zone 300 ps to 5 ns following step transition; ± 1% or less over the zone 5 ns to 100 ns following step transition; 0.5% after 100 ns following step transition. The time base accuracy **shall** be less than 2 ps for delays less than 100 ns.

4.4.4.4 SET2DIL: TDR Requirements The voltage measurement resolution of the TDR unit **shall** be at least 1% of the step amplitude. Step aberrations should be ± 3% or less over the zone 10 ns to 20 ps before step transition; +10%, -5% or less for the first 300 ps following step transition; ± 3% or less over the zone 300 ps to 5 ns following step transition; ± 1% or less over the zone 5 ns to 100 ns following step transition; 0.5% after 100 ns following step transition. The time base accuracy **shall** be less than 1 ps.

4.4.5 TDR Risetime Requirement The procedure depicted in Figure 4-5 can be used to determine the rise time or maximum slope of the TDR measurement system through the probe tip. This is done to ensure that there is sufficient high frequency content within the step pulse that is to be injected into the device under test (DUT) for the respective test method.

Note: The SIU is a static isolation unit designed to eliminate static damage to the TDR sampling head. It may be included within the TDR instrumentation.

4.4.5.1 EBW Risetime The rise time (10%-90%) for EBW **shall** contain sufficient spectral content as agreed upon between vendor and customer base on the printed board application with the open tip of the probe. For EBW, hold the probe in air see Figure 4-5 and measure the maximum slope of the rise time of the step response (in Megavolts/second) and/or the risetime. This value should be compared to the

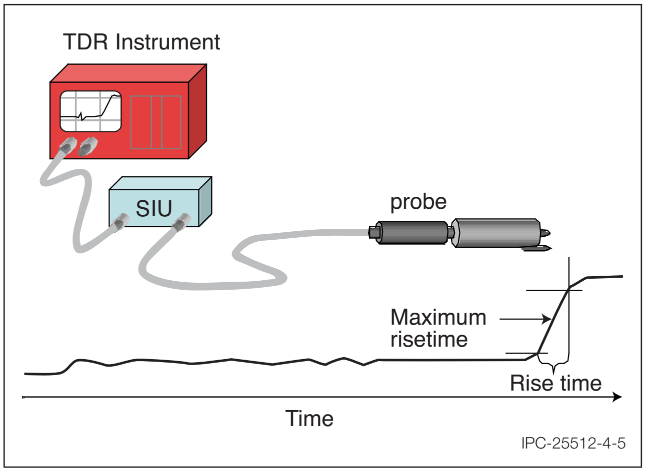


Figure 4-5 Measurement of Maximum Slope of Step Risetime at Open End of Probe

EBW requirements agreed upon between customer and vendor.

4.4.5.2 RIE Risetime The rise time (10%-90%) for RIE **shall** be 250 ps or as agreed upon between vendor and customer with an open tip of the probe as illustrated in Figure 4-5.

4.4.5.3 SPP Risetime The rise time (10%-90%) for SPP **shall** be 11 to 35 ps or less at the open tip of the probe or cable connector as illustrated in Figure 4-5. SPP has an additional requirement of an impulse forming network to be located between the TDR head and the test probe.

4.4.5.4 SET2DIL Risetime The rise time (10-90%) for SET2DIL **shall** be <35 ps at the open tip of the probe or cable connector as illustrated in Figure 4-5.

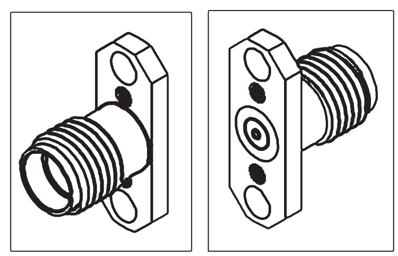
4.4.6 TDR Impedance The impedance of the TDR unit should be 50 Ω with an impedance uncertainty less than or equal to ± 0.5 Ω.

4.4.7 TDR System Calibration Follow the TDR instrument manufacturer's recommendation for the frequency of factory calibration. Since RIE is related to the ratio of loss, field calibration reverts to insuring proper results from calibration standards.

4.4.8 SPP Impulse Forming Network Requirement The pulse width at the output of the IFN observed at the probe tip **shall** be a minimum of 20 ps. The recommendation is to have a 20 ps to 60 ps pulse width detected in TDT through the measurement set-up on typical line lengths used in the test coupon.

4.4.9 Printed Board Connectors The TDR cable connection **shall** utilize a ''SMA,'' 3.50 mm, or 2.92 mm connectors at their measurement ports. It is recommended that cable connections be tightened with a torque wrench to follow specifications, unless otherwise specified by the manufacturer of the connector or cable.

Three general probing solutions may be utilized to perform the SPP extraction: microprobe pads, SMA connectors, and handheld probes. Surface-mounted SMAs, as shown in Figure 4-6, are recommended for SPP. They may be either bolted or slip-fitted into the alignment holes as explained earlier. The bolt-down specification for a Molex SMA style connector, part number 73251-1850, is shown in Figure 4-6.



Connecter Type	Required Torque
SMA	5 in-lb (0.56 N-m)
3.50 mm 2.92 mm	8 in-lb (0.90 N-m)

IPC-25512-4-6

Figure 4-6 Bolt Down Torque Requirement for 2 Connector Styles

4.4.10 TDR Cabling All test cables **shall** meet the following minimum specifications:

a) Coaxial with a 50 ±1 Ω characteristic impedance
b) 2.92 mm, 3.50 mm, or SMA connectors
c) Max cable insertion loss ≤2.50 dB at 65 GHz, 50 GHz, 40 GHz, or 26.5 GHz, respectively
d) Probing insertion loss ≤0.33 dB at 65 GHz, 50 GHz, 40 GHz, or 26.5 GHz, respectively

4.4.11 TDR ESD Protection TDR equipment **shall** provide ESD protection commensurate with the test environment.

It is recommended that samples be grounded to remove any residual static to protect against static discharge with in the test environments.

Static can be built up on samples prior to test and can damage the sampling heads in the TDR/TDT equipment. Therefore, it is recommended that ESD protection be used. Such protection must be supplied internally to the TDR system. Samples should be grounded to remove any residual static and/or passed through some type of deionization device prior to testing. This can be done by shorting each line to ground with a simple connection between one end of the lines and the instrument ground. Keeping the relative humidity in the test area between 45% and 55% may minimize the buildup of static. Operators are always required to have a grounding strap around one wrist having a 1 MΩ resistor in series with it. Special waxing can be used on the lab floor to prevent body charge build-up. Always use a grounded, conductive table mat. Always wear a heel strap. Always ground the center conductor of a test cable before making a connection to static-sensitive equipment.

4.5 SPP Test Apparatus

4.5.1 Other SPP Equipment Requirements An LCR meter is required that can measure capacitance at 1 MHz.

4.5.2 SPP Software The following software is required for implementation of the SPP technique:

a) Gamma-Z software for signal processing or equivalent
b) 2D field solver such as CZ2D, which can be downloaded from: www.alphaworks.ibm.com/tech/gammazandcz2d, or equivalent

4.6 FD Test Apparatus The measurement equipment needed includes a VNA, cabling, a probing solution, and a calibration structure and calibration coefficients that are acquired from the probe or connector manufacturer. The probing solution should match the test sample chosen from the above described samples. High performance connectors and cables are recommended in performing VNA measurements. Optionally, a TDT system may be used in place of a VNA to acquire frequency domain attenuation and loss data.

5 Procedures

5.1 EBW Measurements Procedure

5.1.1 Measurement Process This procedure will measure the maximum slope of the rise time of the combined measurement system and DUT and determine a loss factor. Recommended resolution is 4000 points with a horizontal scale of 200 ps/div.

Step 1 – Probe the interconnect (see Figure 5-1) and measure the maximum slope of the step response in Megavolts/second (e.g., 430 Megavolts/second). The maximum slope may be directly acquired from TDR equipment with that capability.

Step 2 – Report the Loss Factor at the test system bandwidth (as measured within 4.4.5.1) (e.g., 430 Megavolts/second @ 14.5 GHz).

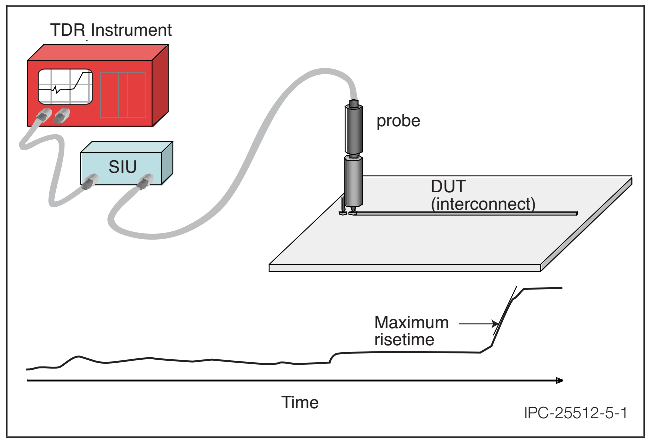


Figure 5-1 Measurement of Maximum Slope of Step Rise Time at Open end of DUT

5.2 RIE Measurement Procedures Figure 5-2 summarizes the RIE measurement procedure.

The RIE method utilizes a comparison between a reference loss (line) measurement and a test conductor (line) measurement. The reference measurement may be a calibration standard or short length of conductor in the neighborhood and on the same layer as the conductor to be measured.

5.2.1 TDR – Open or Unterminated Line Requirement The RIE method requires a measurement of lines where one end is a probe launch and the other end is left unterminated or open. The probe injects a fast step at the launch point in much the same manner specified in IPC-TM-650, Method 2.5.5.7. The injected step causes a wave to propagate down the line; most of the wave is reflected by the open end of the line and travels back to the source where it is measured as the superposition of the incident wave and all the reflections.

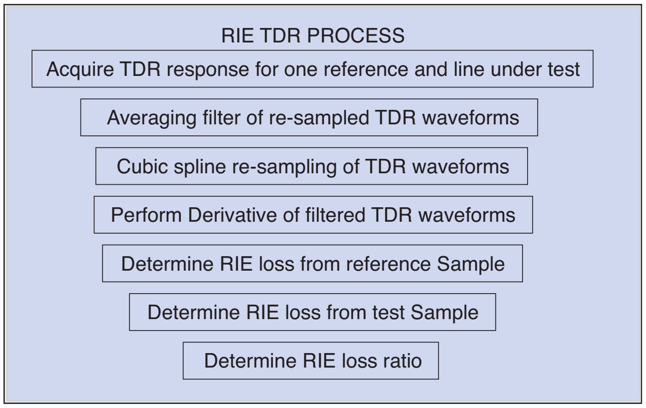


Figure 5-2 RIE Flowchart

These are the TDR waveforms used in the RIE loss calculation.

It is recommended to be positioned within 80% of the vertical screen scale in reference to the representative waveform. The signal on the screen must have a resolution of at least 5% of the measured signal.

Figure 5-3 specifies two time regions. T0 and T1. The sum of T0 and T1 represents the time range for the captured waveform. Figure 5-3 specifies the point between T0 and T1 which corresponds to the point where the probe contacts the printed board, or where the rising edge would be if the probe were disconnected from the sample. The TDR specification for T0 and T1 is found in Table 5-1.

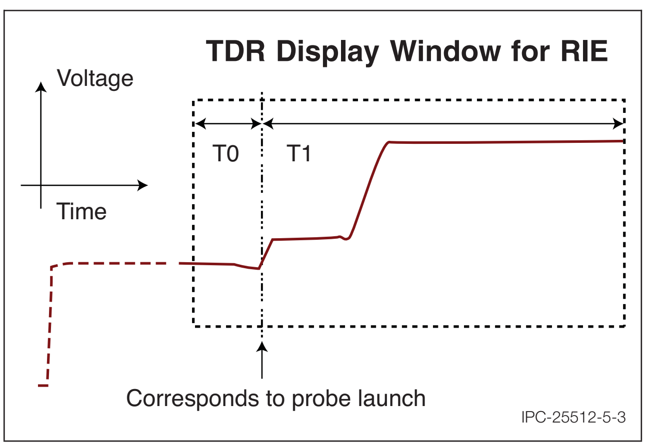


Figure 5-3 Waveform Position on TDR Screen

Each TDR waveform is averaged on the TDR instrument at least 16 times. The time base and offset remain the same for all measurements.

Table 5-1 RIE TDR Time Range Specifications

T0	50 ps (typical)
T1	At least twice the transit delay

5.2.2 Measurement and Processing Two TDR waveforms are captured. One corresponds to a reference and the second corresponds to the test line.

The measured waveforms require post-processing. TDR waveform is processed as follows:

a) Filtering

b) Cubic spline fit

c) Using derivative to find impulse response

d) Calculating RIE loss ratio

5.2.2.1 Recursive Digital Filtering of Spline Data The two TDR waveforms are filtered using the method prescribed in Equation 5-1.

$$\begin{gathered} \text{Let } S_{j,0} = A_j \\ \text{for } k = 1 \text{ to } N \\ \left| \; S_{j,k} = \frac{S_{2,k} + \sum_{i=1}^{j}\left(2^{i-1} \cdot S_{i,k}\right)}{2^j} \right. \\ \text{Assign } B_j = S_{j,N} \end{gathered} \qquad [5\text{-}1]$$

Where:

N is the number of filtering iterations
A_j is the j^{th} point of the on of the acquired TDR waveforms
Sj,k is the j^{th} point of the k^{th} filtered waveform
j is an index for the waveform points
Bj is the j^{th} point of the filtered waveform

The number of filter iterations depends on the number of samples in the acquired TDR waveform and specified in Table 5-2.

5.2.2.2 Resampling with a Cubic Spline Fit The next step is to resample the filtered TDR data to 10,000 points (J). This is accomplished with a cubic spline fit.

5.2.2.3 Impulse Response The impulse response of the reference and test specimen, respectively I_R_j and I_T_j is calculated by taking the derivative of the respective resample step waveforms RB_j and TB_j. One method to perform this

Table 5-2 Filter iterations, N, vs. number of points, n, in TDR capture

Number of Points in TDR capture (n)	Number of Filtering Iterations (N in Equation 5-1)
0 > n ≥750	1
750 > n ≥1500	2
1500 > n ≥3000	6
> n >3000	21

operation is specified in Equation 5-2.

$$I\_R_j = \frac{RB_j - RB_{j-1}}{t_j - t_{j-1}} \qquad I\_T_j = \frac{TB_j - TB_{j-1}}{t_j - t_{j-1}} \qquad [5\text{-}2]$$

5.2.2.4 RIE Results The reference structure, $RIE_{reference}$, is the square root of the square of the integral of the square of the impulse response I_R, and can be calculated from J samples as show in Equation 5-3. The test structure, RIE_{test}, is the square root of the square of the integral of the square of the impulse response I_T, and is calculated from J samples as show in Equations 5-3 and 5-4.

$$RIE_{reference} = \sqrt{\sum_{j=1}^{J} I\_R_j^{\,2}(t_1 - t_0)} \qquad [5\text{-}3]$$

$$RIE_{test} = \sqrt{\sum_{j=1}^{J} I\_T_j^{\,2}(t_1 - t_0)} \qquad [5\text{-}4]$$

The RIE loss in dB, RIE_{loss_dB}, is calculated by dB ratio of the RIE_{test} to $RIE_{reference}$ as show in Equation 5-5.

$$RIE_{loss\_db} = 20 * \log\left(\frac{RIE_{test}}{RIE_{reference}}\right) \qquad [5\text{-}5]$$

5.3 SPP Procedure Figure 5-4 summarizes the SPP measurement extraction process.

5.3.1 Selecting Optimum SPP Transmission Lines SPP utilizes measurements on two lines of different lengths such as 2.0 cm and 8.0 cm. The pair **shall** be designed to be identical in every way except for length. The SPP is used to extract parameters such as α(f) β(f), Γ(f) and Z_0(f) by utilizing the difference between the two specimen line lengths. Effects due to the connectors, cables, probes, and oscilloscope circuitry can be minimized using this method. Screening the two lines improves accuracy. Figure 5-5 illustrates lines of similar design. Accuracy is improved when the slope and deviation

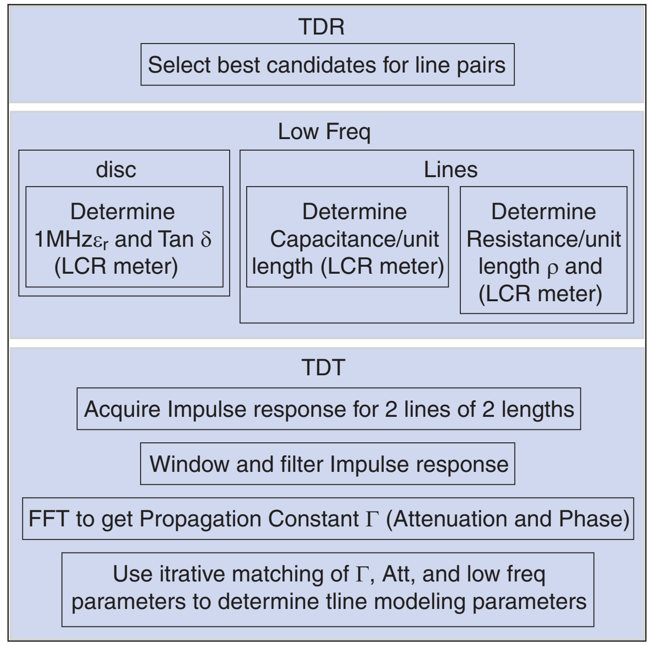


Figure 5-4 SPP Flowchart

along the lengths of overlaid portions of the respective TDR waveforms are coincident.

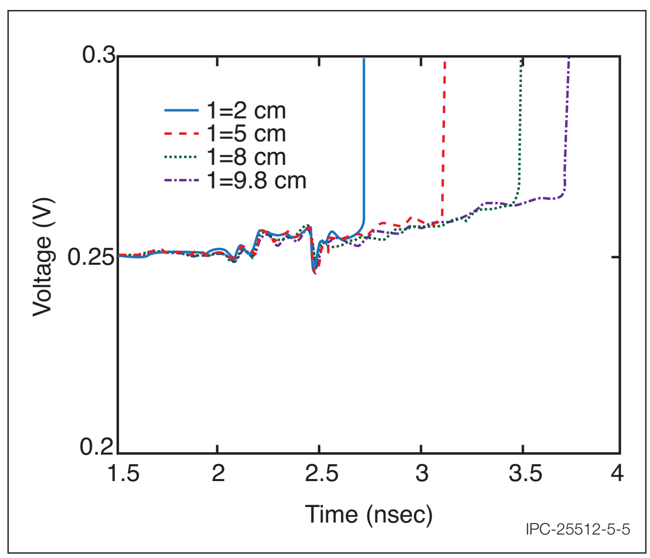


Figure 5-5 Example of Similar TDR Responses for Different Lengths of Lines

5.3.1.1 Additional SPP Step for Differential Lines There are a few additional steps needed when analyzing differential lines. The TDR screening still needs to be performed first. In this case, the screening has to be done for odd-mode, with TDR pulse polarity of + -, and even-mode, + +. It is also recommended to perform TDR for +0 and 0+ single mode to see how close to each other the two lines' characteristics are.

5.3.2 Measuring Frequency Relative Permittivity with SPP The capacitance **shall** be measured at 1 MHz with an LCR meter for several lengths of lines. Such measurements are generally made at a low enough frequency such as 1 MHz so that the reactance associated with the lead inductance is negligible. In a subsequent step line resistance measurements using a 4 wire Kelvin method are also made. The measurements determine the resistance per unit length and the capacitance per unit length. By taking the difference between results at two lengths and dividing by the difference in lengths, the effect of parasitic end load is eliminated. The LCR meter **shall** be also used to measure the capacitance between the layers of the large circular disc designated for dielectric permittivity determination.

Relative permittivity, ε_r, is calculated with Equation 5-6 using the known area, *A*, of the test specimen disc, the distance between the layers *h*, and the capacitance, *C*, as measured with the LCR at 1 MHz. The value for ''*h*'' may be determined by cross-sectioning analysis.

$$\varepsilon_r = \frac{hC}{\varepsilon_0 A} \qquad [5\text{-}6]$$

5.3.3 Measuring Low Frequency Copper Resistivity, ρ, with SPP The resistivity (ρ) per unit length of the signal line conductor is determined with Equation 5-7. R_l is the resistance measured using a 4 wire Kelvin method for the long line of length l_l. R_s is the resistance measured using a 4 wire Kelvin method for the short line of length l_s.

$$\rho = \frac{(R_l - R_s)A}{l_l - l_s} \qquad [5\text{-}7]$$

A is the cross-section area (equal to the conductor width multiplied by the conductor thickness).

5.3.4 SPP Low Frequency Permittivity It should be noted that the two ground planes that are above and below the signal of interest are always shorted together, in the transmission line region and in the parallel plate disc area. The disc that is used should have a diameter that is 100x the height, h to, the nearest ground in order to be able to calculate ε_r directly from (1) without any fringe capacitance consideration. The typical diameter of the disc is 12.7 mm [0.5 in]. It is useful to have a dummy structure that is nearby the disc that has only the via connection between the surface pad and the disc and the small lateral line extension. Typical configuration was shown in 3.3.4.2. The capacitance of this parasitic structure is subtracted from the total disc C so that the end effects are not included in the result for ε_r.

Finally, the dielectric loss, tanδ, is also measured for the large disc using the same LCR meter in the range of 10 KHz to 1 MHz.

The line capacitance per unit length, together with the cross sectional dimensions can also be used for determining the dielectric constant at 1 MHz. The procedure is to calculate the capacitance with a 2D field solver for an assumed dielectric constant. Iteration is used on this assumed value until the agreement is obtained between measured and calculated C. The implicit assumption here is that the lines are uniform and that the cross section is well known along the length. Both these assumptions have limitations and this is why the extraction based on line C is not as accurate. On the other hand, the composition of glass fiber and dielectric resin might differ in the disc area from the line area which could introduce errors in the extracted ε_r at 1 MHz.

5.3.5 SPP TDT Measurement TDT measurements are also made with several lines, but especially with the 2 cm [0.787 in] and 8 cm [3.15 in] lines of interest. In addition, it is useful to measure a very short line of ''zero length,'' (e.g., 0.25 - 0.45 mm [0.0098 - 0.0177 in]) in order to obtain the bandwidth of the time-domain set-up and for use as a reference for delay extraction. The TDT measurement monitors the propagation delay at 50% of the signal swing, the propagated rise time between 10% and 90% levels. By taking the difference in delays for the two lines and dividing by the difference in lengths, one obtains the line propagation delay per unit length, τ, without the effect of probes, pads, and via discontinuities. The assumption is that these features are of similar characteristics for the two lines. The propagated risetime through the ''zero length'' line indicates the bandwidth for the setup based on the simplified formula for the upper 3 dB frequency given in Equation 5-8.

$$f = \frac{0.35}{tr} \qquad [5\text{-}8]$$

The correlation of propagation delay and rise time shape with simulation can provide a very useful validation of the broadband model that is being created using this method. Examples are given in Figure 5-6.

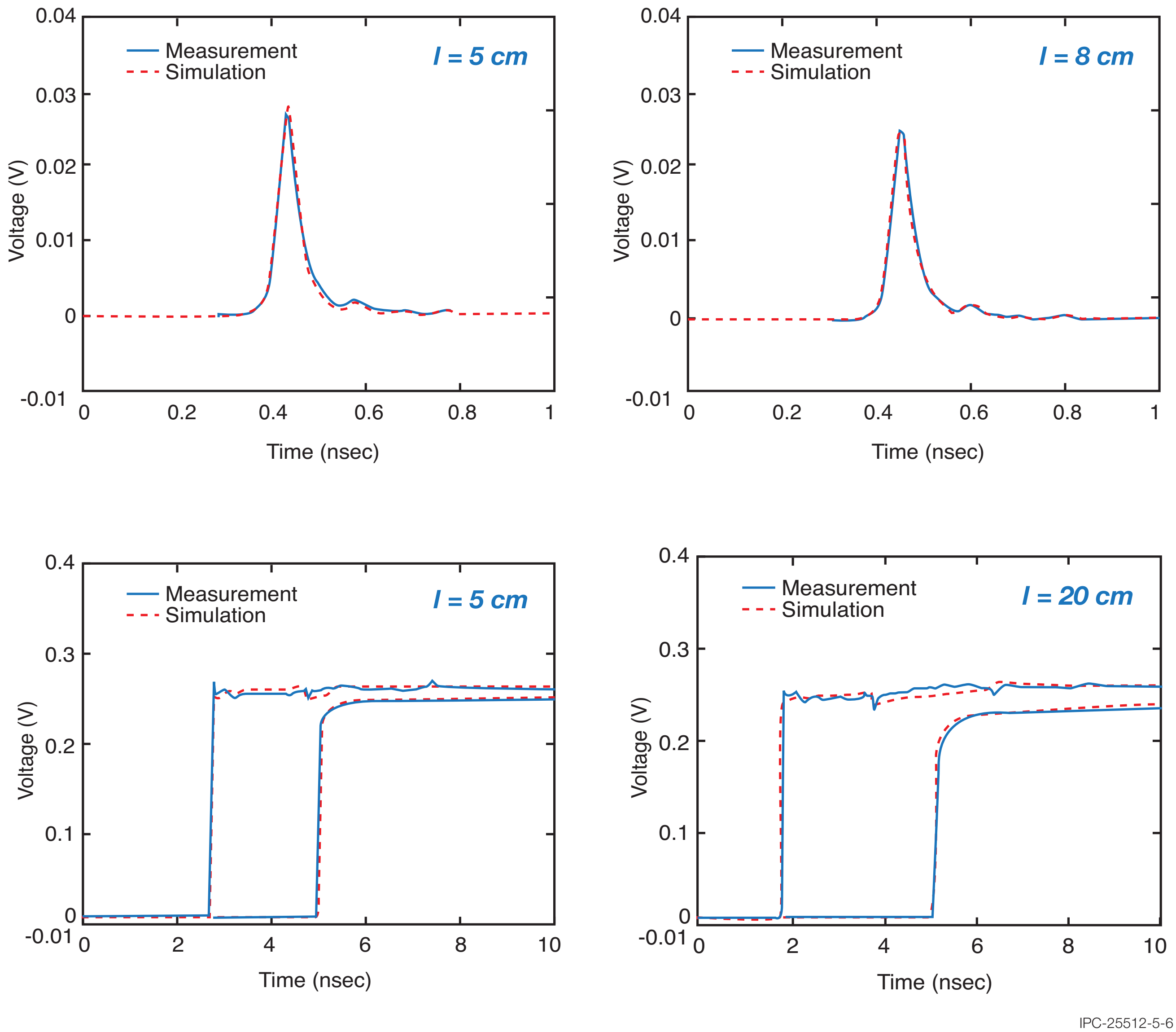


Figure 5-6 Typical TDT Measurements and Validation

Both narrow pulse and step-source propagation measurements are compared with the simulations. Dielectric losses become significant mostly on longer lines, while short duration pulses propagated on shorter lines highlight the good agreement for the high-frequency fit. The agreement in both cases, both in timing and signal amplitude and shape, perform the complete validation. In addition, propagation delay measured on a medium length line, such as 5 cm where losses are not very strong and end effects are not too significant, can provide an approximate calculation of ε_r. This is an approximate value because the lines are not ideal, losses are present, and the signal is broadband. However, it gives a bound on the value of ε_r that indicates that the disc extraction is not totally incorrect. The ideal dielectric is then obtained from Equation 5-9.

$$\tau = \frac{\sqrt{\varepsilon_r}}{c} \qquad [5\text{-}9]$$

where τ is the propagation delay per unit length obtained from TDT and c is the speed of light in a vacuum. As indicated before, printed board technology could have fairly large dimensional tolerances. This is why it is advisable to perform as many validations of the extracted material parameters as possible with various approaches, such as the large disc, the line C, and the TDT-based delay.

5.3.6 SPP Short-Pulse Measurement The final type of electrical measurement is where the technique gets its name. Pulses of high-frequency content are sent through the conductors, and the output is measured and digitally captured. A short pulse is created by differentiating a step function. Most sampling oscilloscopes have suitable step function generation capability for the general purpose of TDR. Simple passive differentiator networks can be placed in-line with the source cable connecting to the coaxial probes or connectors injecting signal into the printed board. Newer rise time-enhancing amplifiers can also be placed in-line before the differentiator to extend the measurement bandwidth. Measurements can be made with coaxial probes or SMA connector interfaces. A digitized pulse is measured on each of two lengths of identical transmission lines. Sample results are shown in Figure 5-7.

Care needs to be taken to use the highest appropriate bandwidth cables, probes, adapters; the smallest and shortest vias, the smallest pads; highest bandwidth detector circuit; and fastest differentiator (IFN).

Pulses are measured with 512 to 1024 point resolution. The recommendation is to have 1024 points of timing resolution. It is acceptable to concatenate captured frames to achieve this.

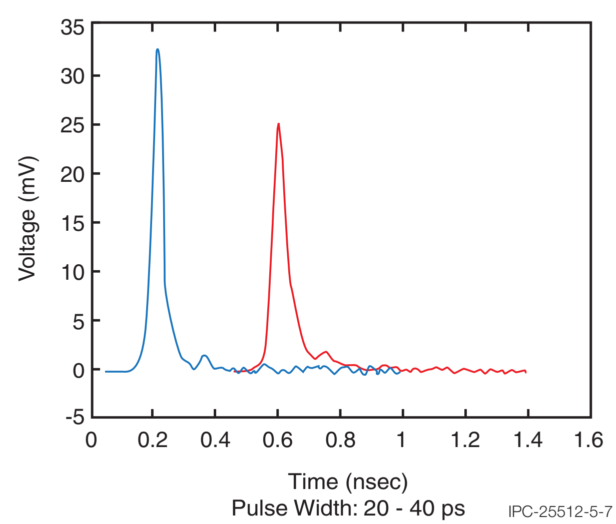


Figure 5-7 Typical Short Propagated Pulses

Typical oscilloscope time base settings are in the range of 25-75 ps/div, depending on the equipment used and length of lines. The vertical scale is set to maximize use of the screen while ensuring the entire waveform is captured. It is recommended that captured waveforms consist of 256 averages.

Pulses are generally shifted toward the left of the oscilloscope screen with just enough of a base DC portion to establish the correct base reference level. A good rule of thumb is to have the peak of the pulse reside at the 2nd major horizontal division on the screen. The inclusion of the right hand tail of the signal permits the capture of as much low frequency spectral content as possible in one frame. The selection of the time per division setting is then a compromise between having very high time resolution for the fast portion of the pulse itself and the need to include the return to ground tail end of the pulse in less than two frames. The use of more than 1024 horizontal points is not recommended.

The signal line impedance is designed to match the measurement environment of 50 Ω, but this is not absolutely necessary. Different impedances are tolerated, but large differences may generate too large of an interface reflection that cannot be eliminated by time-windowing of the Fourier transforms and could also distort the pulse shapes. The above examples are considered extremely clean.

The amplitude of the propagated signal should be maximized through proper contact during probing. If using a probe station, this is accomplished through use of proper down force.

If bolting the SMA connectors on in free space, one needs to position the DUT to ensure the maximum peak signal.

5.3.6.1 SPP Signal Processing

5.3.6.1.1 Level Shifting The first step is to shift the two pulses to a common level. Both pulses are shifted to a 0V level as shown in Figure 5-8. Some pulses will have an initial offset due to excessive DC drop in the system.

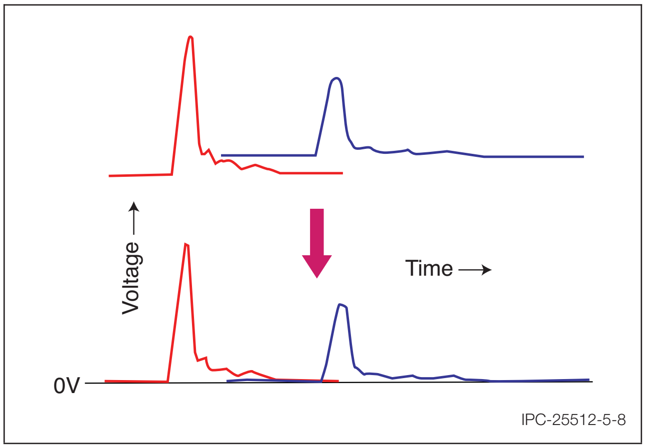


Figure 5-8 Level Shift Pulses

5.3.6.1.2 Time Windowing Time windowing is required before the subsequent step that uses a Fast Fourier Transform (FFT). The two waveform windows are defined as a region of time that starts at the last stable point around 0V for each conductor and ends next to the stable point around 0V on the long conductor, as illustrated in Figure 5-9. It is recommended to first determine the extent of Window 2 for the long line and then use the same extent for the short line, such that Window 1 and Window 2 are identical.

5.3.6.1.3 Time Shifting and Padding The next step is to utilize the window to shift both waveforms by the same delay so that the beginning of Window 1 is at 0 seconds. Subsequently all waveform samples not in the windows are set to 0V and are called padding. Figure 5-10 provides an example.

5.3.6.2 Fourier Transformation The Fourier transform is performed on the two time shifted pulses using the same number of points as were used in the time-shifting and padding step (this is important). The number of points must be a power of 2; a typical number of steps is 8192 or 16384. Re-sampling is normally required to meet this requirement. V1(t) is the shifted and padded waveform that represents the short line of length l_1 and V2(t) is the shifted and padded waveform that represents the long line of length l_2. The FFT of

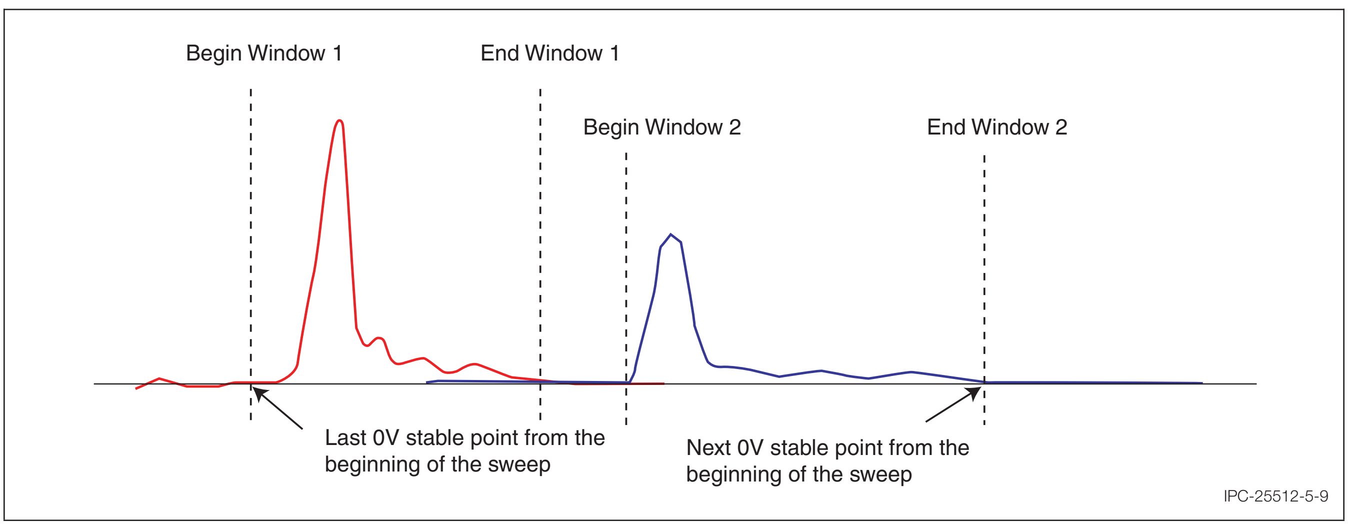


Figure 5-9 Waveform Window Region

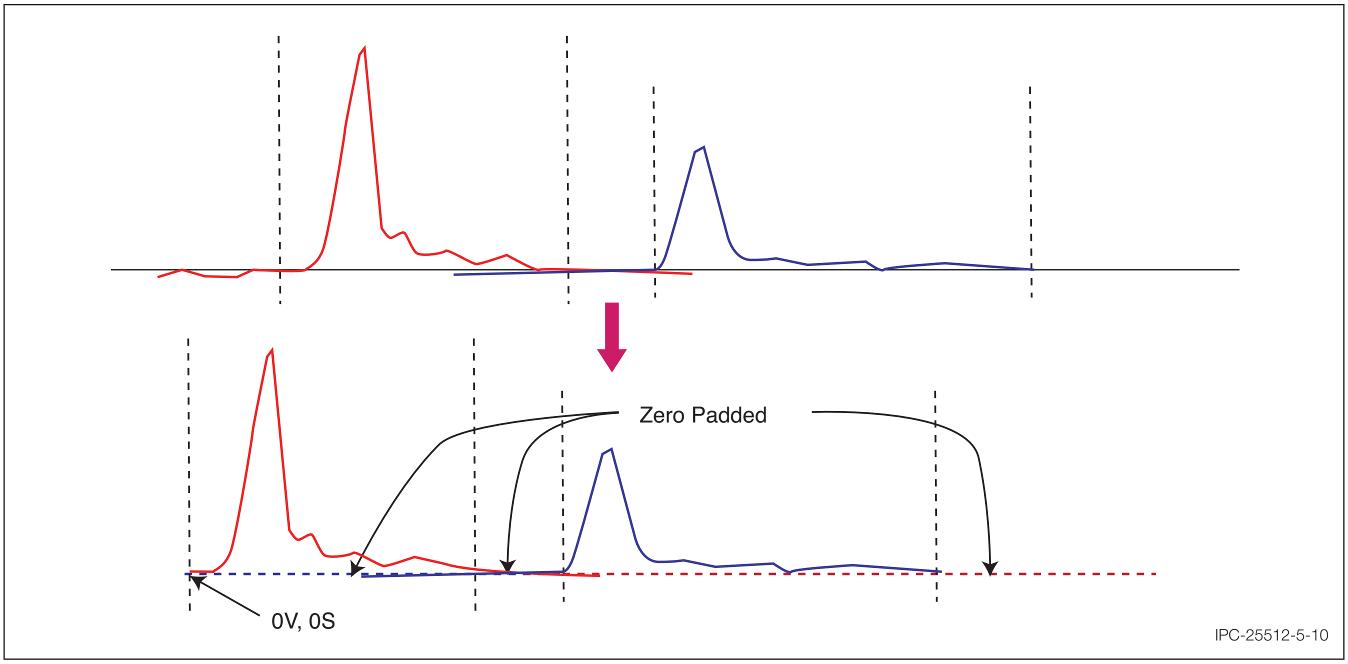


Figure 5-10 Time Shifting and Zero Padding

V1(f) and V2(t) is a respective ordered frequency pair *A1(f)*, ϕ1*(f)* and *A2(f)*, ϕ2*(f)*.

The attenuation, *Att(f)*, and phase constant, β*(f)*, are computed with Equations 5-10 and 5-11.

$$\Gamma(f) = \alpha(f) + j\beta(f) = -\frac{1}{l_1 - l_2} \ln\left(\frac{A_1(f)}{A_2(f)}\right) + j\frac{\phi_1(f) - \phi_2(f)}{l_1 - l_2} \quad [5\text{-}10]$$

$$Att(f) = 20 \log (e^{\mathrm{Re}(\Gamma(f))})$$
$$\beta(f) = \mathrm{Im}\,(\Gamma(F)) \quad [5\text{-}11]$$

5.3.6.3 SPP Broadband Complex Permittivity Extraction

5.3.6.3.1 Frequency Dependent Line Parameters A 2D field solver is used to calculate *R(f), L(f), C(f),* and *G(f)* per unit length based on the actual cross sectional dimensions, the metal resistivity ρ, and low frequency ε_r and tanδ outlined above. A 2D solver that assures a causally related calculation of *L-R* and *C-G* is recommended. The initial calculation can contain a few initial points for ε_r and tanδ that are used as starting values for the high-frequency range, for example 3 GHz to 20 GHz. Based on the calculated *R(f), L(f), C(f),* and *G(f)*, the attenuation and phase constant are calculated from Equation 5-12.

$$\Gamma(f) = \alpha(f) + j\beta(f) = \sqrt{(R + j\omega L)(G + j\omega C)} \quad [5\text{-}12]$$

The measured and calculated attenuation and phase are compared to the measured values as shown in Figure 5-11 and Figure 5-12.

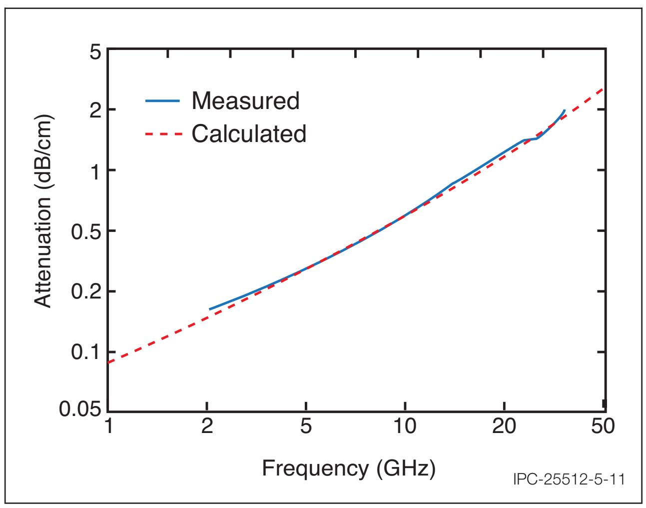


Figure 5-11 Measured and Calculated Attenuation

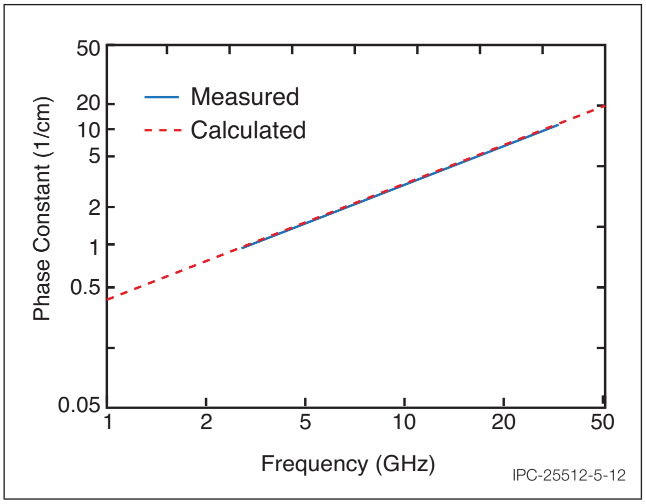


Figure 5-12 Measured and Calculated Phase Constant

The calculation is iterated until good agreement is obtained. Agreement is assessed visually. Each time, the high-frequency values of ε_r and tanδ are modified. It is recommended to use a 2D field solver that has a Debye model for the relation between C and G as described in Equation 5-13 with a large number of poles to cover a broad frequency range. 30 poles are considered a good practice.

$$\varepsilon(\omega) = \varepsilon_\infty + \sum_i \frac{\varepsilon_i}{1 + j\omega\tau_i} \qquad [5\text{-}13]$$

The solver should be able to smoothly interpolate between the low frequency values and the high-frequency ones.

The broadband $Z_0(f)$ is also obtained based on *R(f), L(f), C(f), G(f)* as shown in Equation 5-14.

$$Z_0 = \frac{\Gamma(\omega)}{G(\omega) + j\omega C(\omega)} \qquad [5\text{-}14]$$

An example of such broadband impedance is shown in Figure 5-13.

5.3.6.3.2 Frequency Dependent Complex Permittivity Extraction The final *R(f), L(f), C(f),* and *G(f)* are used to extract the complex permittivity using Equation 1-2 and 1-3.

Some examples of extracted permittivities are shown in Figure 5-14.

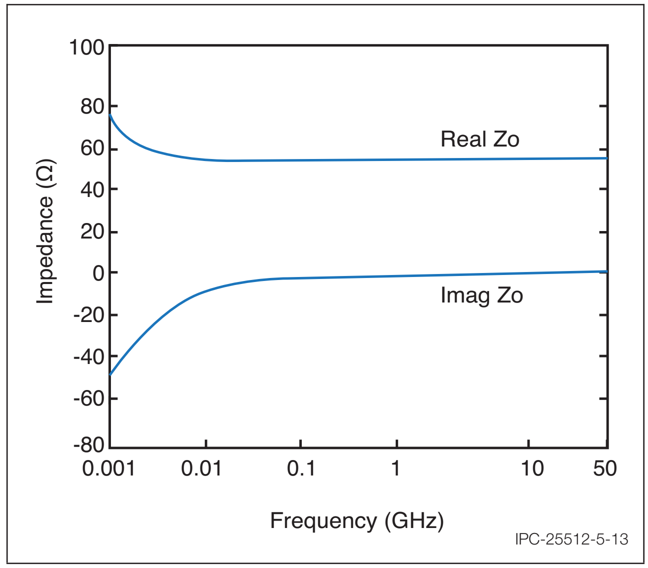


Figure 5-13 Extracted Broadband Characteristic Impedance

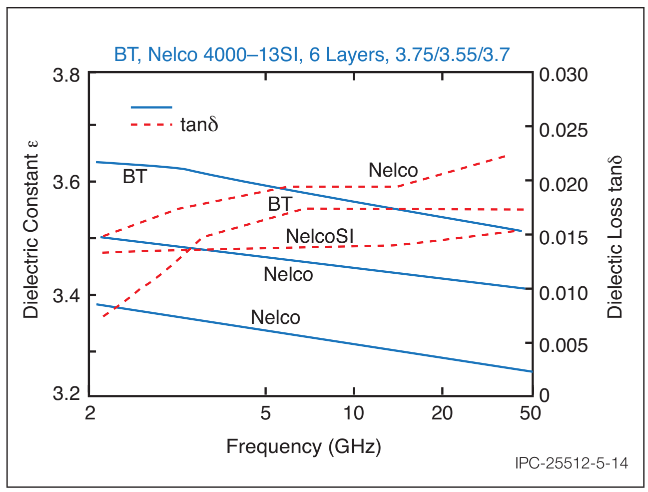


Figure 5-14 Extracted broadband Complex Permittivities

The same technique can be used for extracting the resistive and dielectric losses in the presence of metal roughness and dielectric inhomogeneities and for differential wiring.

5.4 SET2DIL Procedure This specification outlines the fundamental principles behind SET2DIL; the exact method will be instrument-dependent. Vendors providing SET2DIL capability are responsible for ensuring correlation between standard SDD21 measurements (VNA) and their implementation of SET2DIL.

5.4.1 SET2DIL Structure The SET2DIL structure is a 101.6 mm [4.0 in] representative piece of the differential pair (or single-ended signal) being characterized (see Figure 5-15). It has an effective length of 203.2 mm [8.0 in]. A ''thru'' structure is used as a reference (see Figure 5-16).

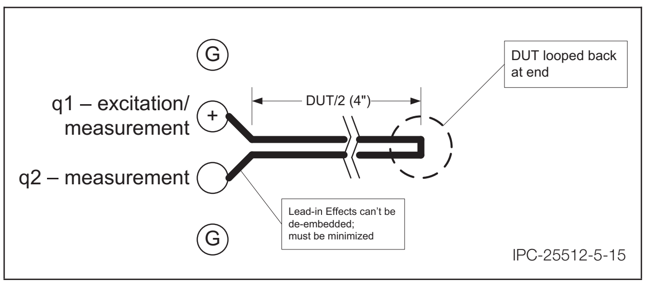


Figure 5-15 SET2DIL Test Structure

5.4.2 SET2DIL Measurement A TDR pulse is injected into ''q1'' while the waveforms at q1 and q2 are monitored. The q1 waveform will represent single-ended impedance with the far end cross talk (FEXT) pulse superimposed on that. Likewise, the q2 waveform will represent the near end cross talk

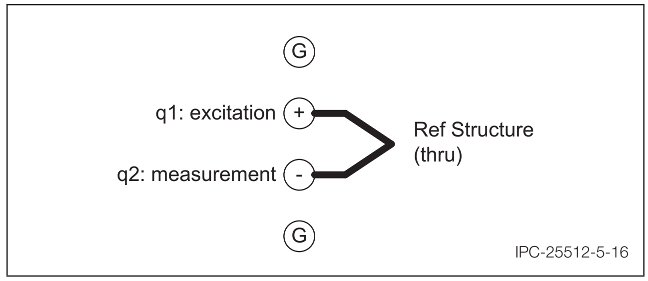


Figure 5-16 SET2DIL "thru" Structure

(NEXT) pulse with the TDT pulse superimposed on that (see Figure 5-17).

5.4.3 SET2DIL TDD21 Extraction The TDT pulse is extracted from the q2 waveform, and the FEXT pulse is extracted from the q1 waveform. FEXT is subtracted from TDT to form TDD21. A detailed description of the waveform manipulation is available as the 2010 DesignCon paper ''SET2DIL: Method to Derive Differential Insertion Loss from Single-Ended TDR/TDT Measurements.'' Figure 5-18 shows the extracted waveforms and the resultant TDD21.

5.4.4 SET2DIL SDD21 Calculation The FFT of the derivative of TDD21 is divided by the FFT of the derivative of the ''thru'' waveforms to calculate SDD21 of the SET2DIL structure. Figure 5-19 shows the time and frequency domain waveforms (SET2DIL frequency domain results compared to VNA measurements on the right). SDD21 as a function of frequency can then be compared to expected values to determine if the printed board construction is adequate to meet the insertion loss requirements of the design.

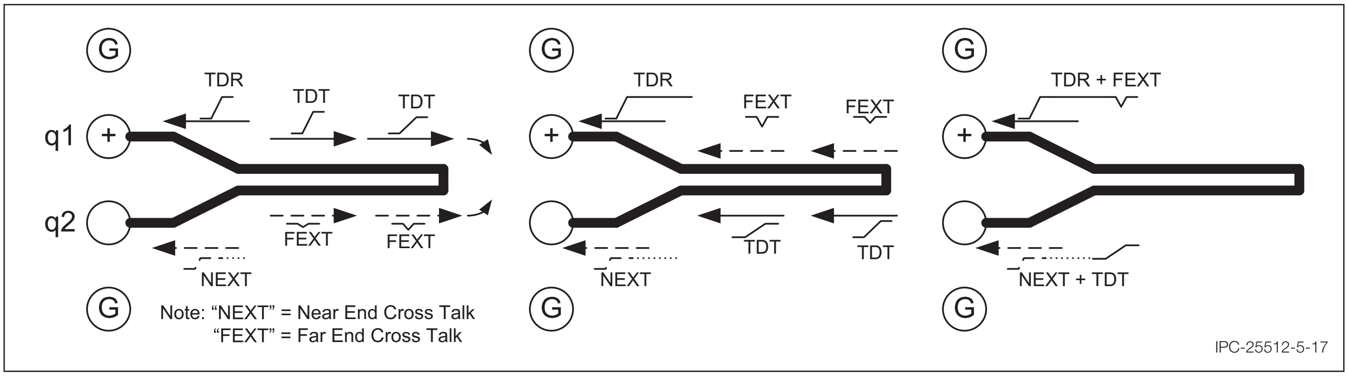


Figure 5-17 SET2DIL Waveforms

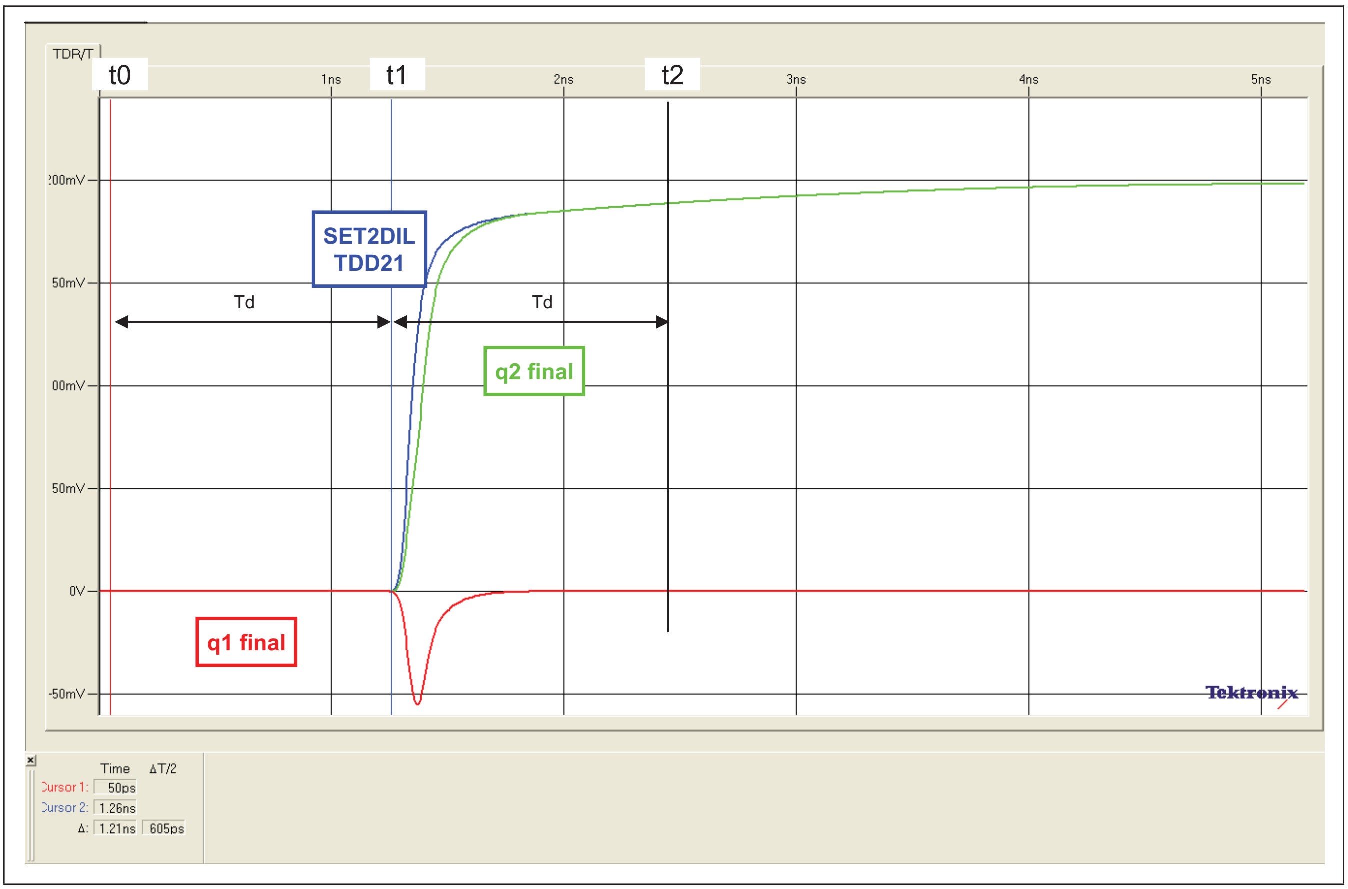


Figure 5-18 SET2DIL TDT, FEXT, and TDD21 Waveforms

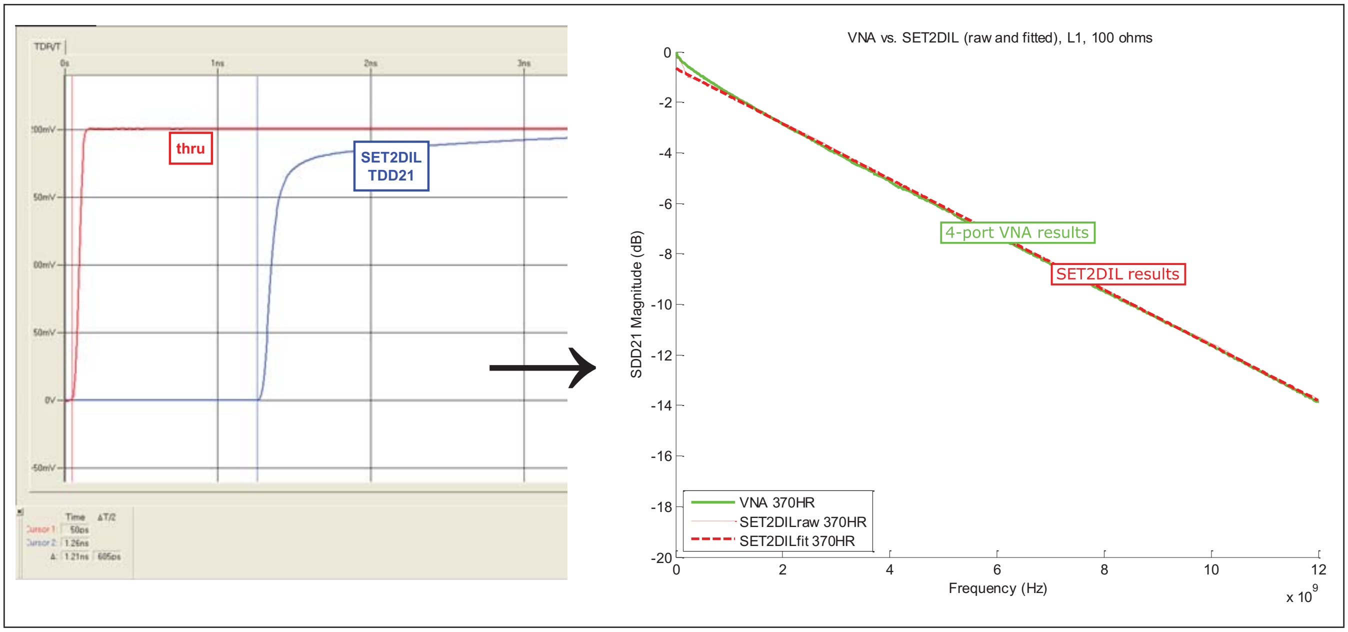


Figure 5-19 SET2DIL SDD21 Calculation

5.5 FD Procedure This specification currently outlines measuring Frequency Domain characteristics using a VNA (Vector Network Analyzer). Optionally, a TDT (Time Domain Transmission) system may instead be used to create the frequency domain loss data. The TDT essentially compares the FFT (Fast Fourier Transform) of a calibration ''through'' to the FTT of the test sample. The output is the S21 scattering parameter matrix.

5.5.1 VNA Settings Recommended settings for the VNA include an IF bandwidth of 1 kHz and a step size of 10 MHz.

5.5.2 VNA Calibration A short, open, load, and through (SOLT) calibration must be preformed to obtain accurate VNA measurement. This calibration **shall** be done at the tip of the probing solution; therefore, the calibration structure will depend on the probing solution used.

5.5.3 FD Measurement Adherence The metric used to determine material ''goodness'' is insertion loss. Insertion loss (IL) is defined as the negative of S21 expressed in decibels. The through scattering parameter, S21, is a direct output from the VNA or a TDT instrument. The insertion loss fit is used to determine passing and failing lines. The slope the Insertion loss fit, ma, can be used as another metric. Figure 5-20 illustrates the insertion loss of a line, the respective fit, and limit regions.

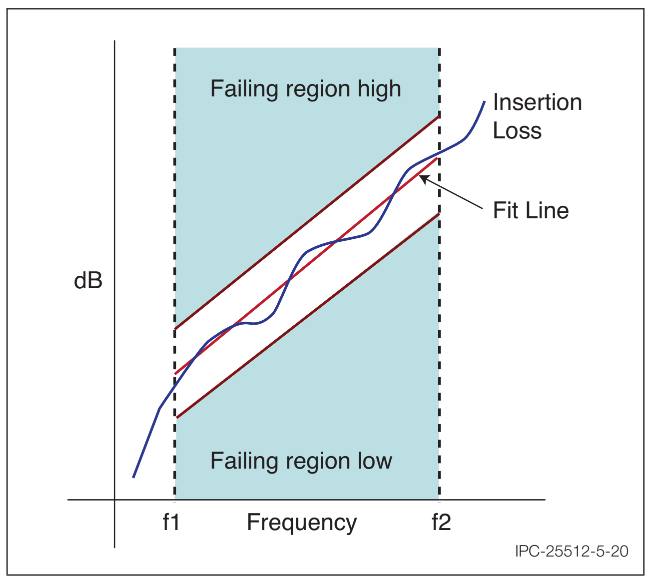


Figure 5-20 Illustration of Insertion Loss Fit and Passing and Failing Regions

The slope, m_a, is representative of the average IL obtained from the test sample. This slope should be less than the slope, m_{spec}, of the pass/fail line that is material dependent.

5.5.4 Calculating Average Insertion Loss Slope m_a and Intercept b_a For ''*N*'' points between frequency range *f*1 to *f*2 the average insertion loss slope and intercept are defined as follows in Equations 5-15 to 5-18.

$$f_{avg} = \frac{1}{N}\sum_{n} f_n \quad [5\text{-}15]$$

$$IL_{avg} = \frac{1}{N}\sum_{n} IL(f_n) \quad [5\text{-}16]$$

$$m_A = \frac{\frac{1}{N}\sum_{n}(f_n - f_{avg}) \cdot (IL(f_n) - IL_{avg})}{\sum (f_n - f_{avg})^2} \quad [5\text{-}17]$$

$$b_A = IL_{avg} - m_A \cdot f_{avg} \quad [5\text{-}18]$$

Suggested values of f1 and f2 are 1 GHz and 5 GHz respectively.

The slope m_a is a measure of the total frequency dependent attenuation, α, which is described in IPC-2141.