Production Test Methodology to Determine High Frequency Signal Loss of PWB Interconnects

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Abstract

A new low cost, simple and repeatable production test method for measuring signal loss of printed wiring board (PWB) interconnects is discussed. The method uses Time Domain Reflectometry (TDR) to measure the transition duration of a step pulse through the PWB interconnect to determine the loss. The loss is presented as an "Equivalent 3dB Bandwidth". Signal components with frequencies higher than the Equivalent Bandwidth frequency will incur more than 3 dB of loss passing through the interconnect. The method presents the total interconnect loss and does not describe loss components individually (e.g., dielectric loss and skin effect loss, etc.). This paper describes the specific process of measurement, a metrology capability assessment, and study results demonstrating the method's ability to use the loss measurements to differentiate among PWB materials and structures.

Introduction

As the concern over signal loss through interconnects becomes greater, the need for PWB manufacturers to test their products for that loss increases. A simple, low cost test method is needed to enable PWB suppliers to understand the high frequency properties of their raw material and to be able to ensure their customers that the high frequency specifications of the PWB interconnects are being met.

This paper proposes a new test method to meet that need. First, the process is described with a step-by-step procedure, and the panels and interconnects used are described. Next, the results of a Metrology Capability Assessment (including a gauge repeatability and reproducibility study) are presented, and finally three-(3) simple but focused studies which use the new test method are summarized.

1) Loss Comparison of Nelco 4000-13 and. Isola FR406
2) Loss Comparison by Interconnect line length
3) Inter-Panel Loss Variations

These studies demonstrate the described method's ability (and limitations) to measure the high frequency loss properties of PWB interconnects with sufficient resolution and repeatability for production testing.

Test Methodology Description

Equipment and Instrumentation – This method utilizes the same equipment and instrumentation as that described for impedance testing with IPC TM-650 2.5.5.7 "Characteristics of Impedance of Lines on Printed Wiring Boards by TDR" Section 4.

Equivalent Bandwidth Method – In this method, the transition duration of the measurement system through the probe tip is measured and then the device under test (DUT) is measured. The transition duration through the DUT is then calculated through the use of the root-sum-of squares formula. Finally, an Equivalent Bandwidth (EBW) is calculated to determine the frequency at which a significant loss occurs through the DUT (i.e., -3dB).

Measurement Calibration Procedure - This procedure will determine the transition duration (TD) of the Measurement system through the probe tip.

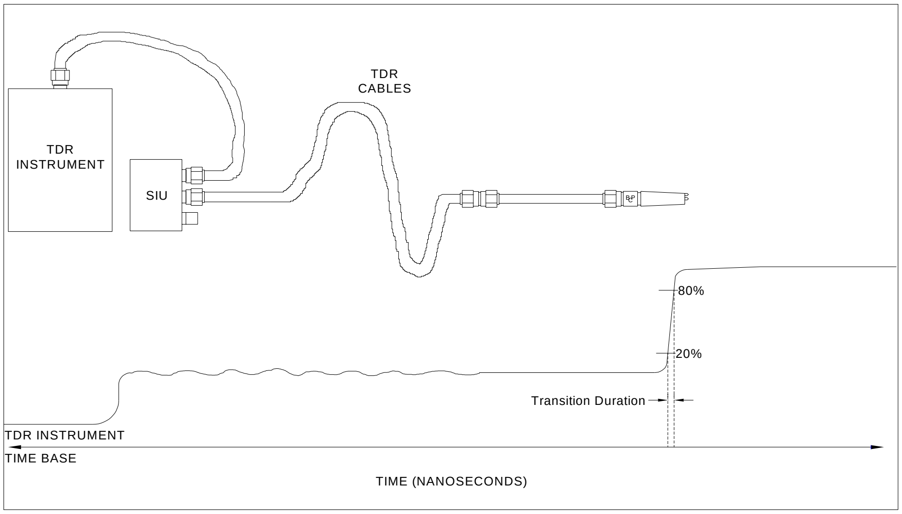

Figure 1 - Measurement of step transition duration at open end of probe.

(Note: The SIU is a static isolation unit designed to eliminate static damage to the TDR sampling head.)

Step 1 - Hold the probe in air (see Figure 1) and measure the transition duration between 20% and 80% of the step response.

Step 2 – Divide the transition duration measurement by two-(2) to calculate the transition duration incident to the probe tip (instead of the TD of the reflected pulse).

Measurement Process - This procedure will determine the transition duration of the combined measurement system and DUT.

Step 1 - Probe the interconnect (see Figure 2) and measure the transition duration between 20% and 80% of the step response.

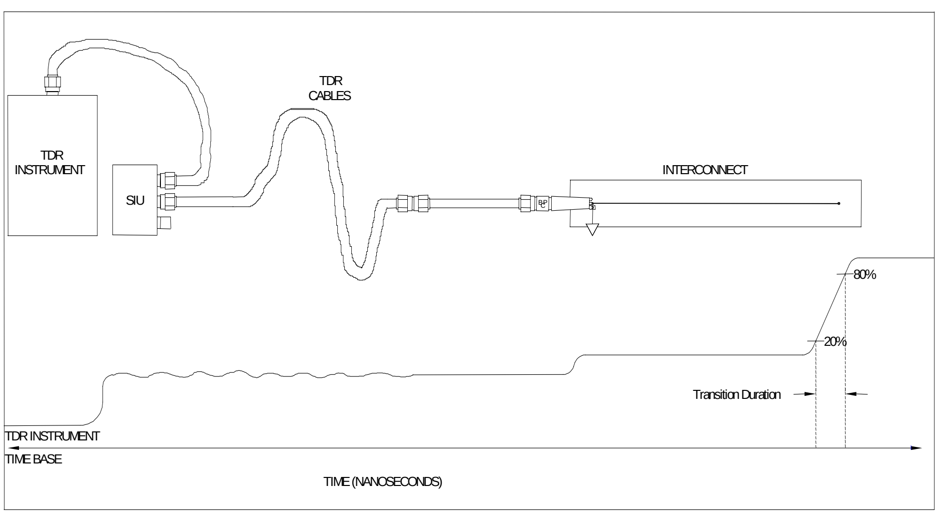

Figure 2 - Measurement of step transition duration at open end of DUT.

Step 2 – Divide the transition duration measurement by two (2) to calculate the transition duration incident to the end of DUT (instead of the TD of the reflected pulse).

Step 3 – Calculate the transition duration of just the DUT by utilizing the root-sum-of-squares formula to remove the response of the measurement system:

Tdut = SQRT ((Tdut + system)^2 - (Tsystem)^2)

Where

Tdut = Transition duration of the DUT

Tdut + system = Transition duration measured at the end of the DUT which includes the response of the measurement system

Tsystem = Transition duration of just the measurement system found at the end of probe

Step 4 - Calculate the Equivalent Bandwidth of the interconnect using

EBW_{-3dB} = K / Tdut

Where

EBW_{-3dB} = The frequency at which –3 dB of attenuation has occurred

K = 0. 223 (assuming a Gaussian pulse – or 0. 221 for a single pole exponential decay)

Tdut = The 20 % to 80 % transition duration of the TDR step response through the DUT

Figure 3 illustrates the concept of Equivalent Bandwidth. The figure shows a Frequency Response curve for a generic DUT. The point where the amplitude of the response has decreased to -3 dB is the Equivalent Bandwidth frequency. A higher Equivalent Bandwidth value means that a DUT will have a better step response to higher frequency signals.

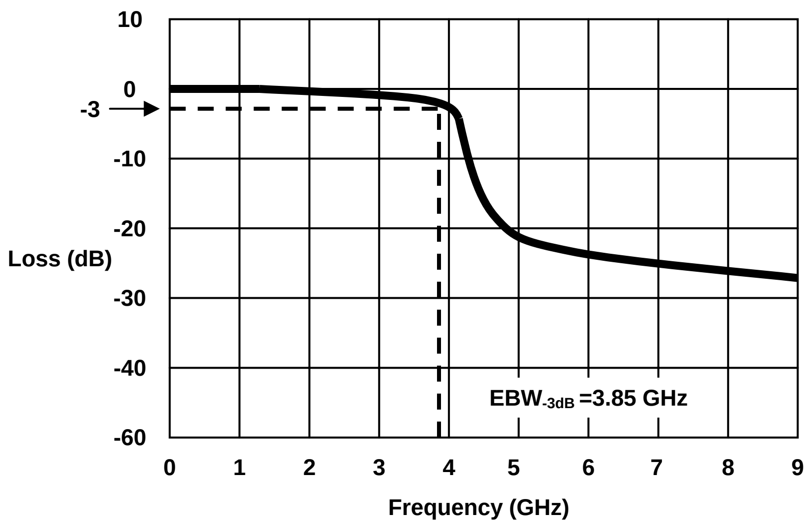

Figure 3 - Equivalent Bandwidth Concept

Test Sample Description - A total of eight sample panels were fabricated. Four (4) of the panels were fabricated using Nelco 4000-13 and another four (4) panels were fabricated using Isola FR406. Copper traces (copper weight/trace height: 0.5 oz) with similar dimensions were formed in each set of four PWBs. All interconnects were designed as per IPC-2141 guidelines for TDR test coupons. Each interconnect was terminated with a via on one end that is suitable for traditional hand probing. The vias were plated thru holes with a 0.045 in. drilled diameter and a 0.041 in. plated finished diameter. The land pads were 0.059 in. in diameter. The pitch between signal via and reference plane via was 0.100 in. The board thickness was 0.091 in. All samples were fabricated by Merix Corporation in Forest Grove, OR.

Angled Interconnects
Nine-(9) traces were formed on each layer. All interconnects were oriented at a 45 degree angle to minimize the variation of loss due to material weave pitch.

Various Interconnect Lengths
To understand the measurement method's ability to discern loss versus trace length the following structures were created:

Table 1 – Various Interconnect Length Sample Description

	Sample Set #1	Sample Set #2
Test Point Name	T1-1 thru 5	T1-16 thru 20
Layer	1	7
Line Width	5.75mil	3.75mil
Lengths	1", 2", 4.5", 7", 12"	1", 2", 4.5", 7", 12"
Orientation	0 Deg	0 Deg

Table 2 – Sample Material Style and Weave

Material	**Isola FR406**	**Nelco 4000-13**
Permittivity (Dk)	3.8(@10GHz-Nominal)	3.70(@10GHz- Split Post Cavity)
Loss Tangent (Df):	0.020 (@10GHz-Nominal)	0.008(@10GHz- Split Post Cavity)
Layer 1		
Pre-preg Weave	2113	2113
Layer 3		
Core Glass Style	1652	2x1080
Pre-preg Weave	2x1080	2x1080
Layer 7		
Core Glass Style	2113	2113
Pre-preg Weave	2116	2116
Layer 9		
Core Glass Style	1080/2113	2x2113
Pre-preg Weave	2116	2116

The solder mask utilized on both boards was Enthone 3241 DSR with the following high frequency properties:

Permittivity (Dk): 3.24@1GHz
Loss Tangent (Df): 0.001@1GHz

Metrology Capability Assessment

General Description
The Assessment comprised three parts including "Accuracy", "Repeatability", and "Reproducibility" carried out over three days.

The measurement equipment used was Introbotics Corporation's Accu-Prober Controlled Impedance Tester (Serial# 8) which includes the following sub-components:

Tektronix TDS8000B Sampling Oscilloscope (Serial#B020733)
Tektronix 80E04 2-channel TDR Sampling Head (Serial# B011203)
Muary Microwave Precision Airline Model 2603A 7mm (Serial# 9222) (Impedance: 49.89 Ohms)
Introbotics IBC100 Probe (Pitch: 100mil) (Calibration: Transfer standard value 50.40 ohms, 20%-80% Risetime Value 17.8 psec)

System Calibration Description

The Accu-Prober system (including the specific probe) was calibrated utilizing the IPC TM-650 2.5.5.7 “Characteristic Impedance of Lines on Printed Wiring Boards by TDR” dated January 2004. The method utilized was the “Transfer Standard Method” (reference section 5.2.1 in IPC document). This method involves calibrating an in-line “transfer” standard (coax cable) utilizing the NIST calibrated Airline as the primary reference. The in-line transfer standard, mounted just adjacent to the probe, is then referenced for each subsequent DUT measurement to ensure accuracy.

Assessment Sample Description

Two interconnects were selected from layer 1. The interconnects were 4.5” long and were fabricated with a 45 degree orientation to the panel edge. The material used was Nelco 4000-13.

Assessment Procedure Description

Accuracy

1) Sixteen (16) measurements were taken on each of the two-(2) interconnects. All measurements were made within a short period of time.
2) The average value of the measurements for each interconnect was assigned as the expected absolute value of the measurement for that interconnect.

Repeatability

1) Fourteen (14) additional measurements were taken on each of the two-(2) interconnects (for a total of thirty-(30) measurements on each interconnect). All measurements were made within a short period of time and on the same day as the previous 16 sets of measurements.

Reproducibility

1) Three operators were used over three days.
2) Each operator took three (3) measurements on each set of the two-(2) interconnects each day over the three (3) days. All measurements were made within a short period of time on each of 3 days.

Precision-to-Tolerance Ratio (P/T)

The P/T ratio is the percentage of specification window that is lost due to measurement error. It is calculated as follows:

$P/T = 100\% * (6 * \sigma) / (USL - LSL)$

Where

σ = The standard deviation in the set of measurements

USL = The Upper Specification Limit - The largest value which can be measured and still be within acceptable tolerance (typically 10% higher than the nominal expected value). For the purposes of this study the USL was set to be 10% higher than the average of the measured values (as no expected value is known).

LSL = The Lower Specification Limit - The smallest value which can be measured and still be within acceptable tolerance (typically 10% lower than the nominal expected value). For the purposes of this study the USL was set to be 10% lower than the average of the measured values (as no expected value is known).

Results

Accuracy

Table 3 - Measurement Results of Accuracy Study

Test Point Name	EBW_{-3db} Expected Value	Std Dev
T6-1	3.359	0.007
T6-2	3.403	0.005

Largest EBW_{-3db} Std Dev: 0.007 GHz
Largest Precision vs. Tolerance (P/T): 6.2 %

Repeatability

Table 4 - Measurement Results of Repeatability Study

Test Point Name	EBW_{-3db} Average Value	Std Dev
T6-1	3.358	0.006
T6-2	3.408	0.007

Largest EBW_{-3db} Std Dev: 0.007 GHz
Largest Precision vs. Tolerance (P/T): 6.0 %

Reproducibility

Table 5 - Measurement Results of Reproducibility Study

Test Point Name	EBW_{-3db} Average Value	Std Dev
T6-1	3.433	0.036
T6-2	3.439	0.041

Largest EBW_{-3db} Std Dev: 0.041 GHz
Largest Precision vs. Tolerance (P/T): 35.9 %

The results show that the Equivalent Bandwidth method of determining loss can be used effectively in a production environment. The Precision to Tolerance Ratio (P/T) for Reproducibility is larger than desired and will continue to be addressed in follow-on investigations. Specific areas of investigation include: probe placement on/within the via, via size, the limits needed for the P/T, and the use of P/T where the measurement need only be greater than a minimum value. The use of fixture based or robotic test systems will significantly improve the repeatability of production test data.

Study 1 Comparison of Nelco 4000-13 vs. Isola FR406

<u>Description</u>

A study was done to compare the measured loss of surface microstrips (Layer 1) for the two different materials, and for striplines (Layer 3) for the same two materials. Thirty measurements were taken and then averaged for each interconnect. EBW_{-3db}, impedance, flight time, velocity and effective dielectric were recorded/calculated.

Table 6 - Sample Description for Study 1

	Sample #1	Sample #2
Test Point Name	T6-1	T6-10
Layer	1	3
Line Width	7mil	6mil
Length	4.529 inches	4.529 inches
Orientation	45 Deg	45 Deg
Materials	Isola FR406 & Nelco 4000-13	Isola FR406 & Nelco 4000-13

Results

The following tables and plots show the measured results. The results clearly indicate a loss difference between the two materials on both surface microstrips and inner layer striplines. The repeatability of the measurement is also clearly sufficient to facilitate the accurate discernment of the use of each material in the PWB construction for a specific trace.

Table 7 – Measurement Results for Material Comparisons Layer 1

Measured Parameter (Averaged from 30 samples)	**Isola FR406**	**Nelco 4000-13**
Average EBW (GHz)	3.00	3.36
Single Sigma (GHz)	0.008	0.005
P/T (utilizing 6-sigma and a tolerance window of +/-10%)	8.4	4.6
Average Impedance (Ohms)	47.29	50.00
Average Effective Er	3.56	3.23
Average Flight Time (pseconds)	765	732
Average Velocity (pseconds/inch)	159.8	152.3

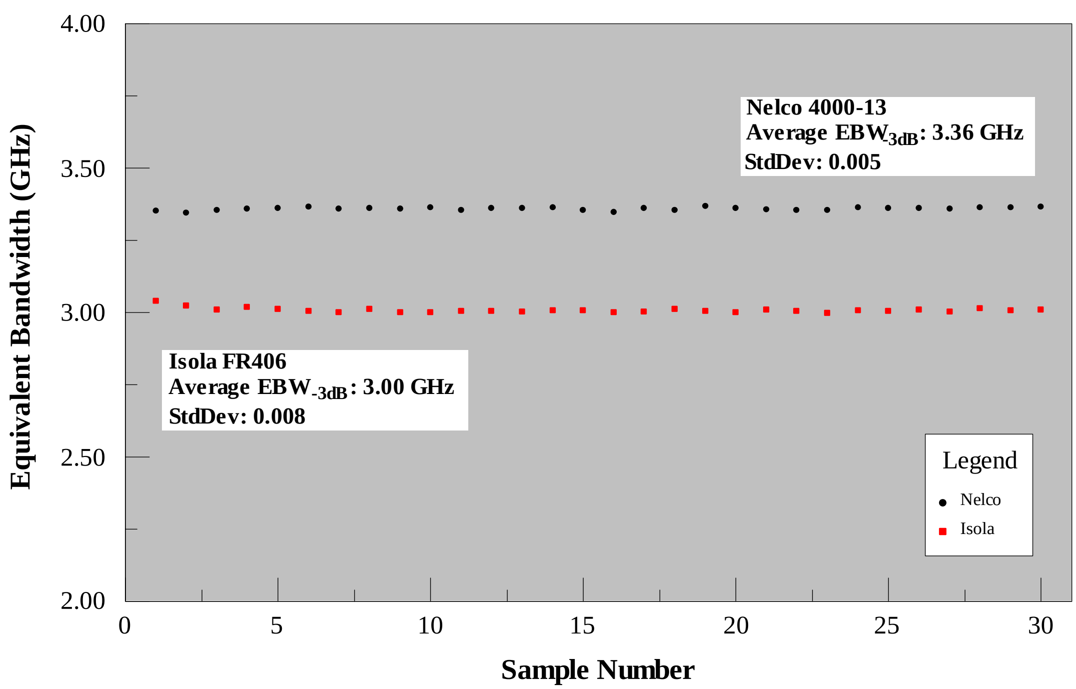

Figure 4 - Layer 1 Material Loss Comparison

Table 8 – Measurement Results for Material Comparisons Layer 3

Measured Parameter (Averaged from 30 samples)	Isola FR406	Nelco 4000-13
Average EBW (GHz)	3.10	3.37
Single Sigma (GHz)	0.005	0.005
P/T (utilizing 6-sigma and a tolerance window of +/-10%)	4.99	4.89
Average Impedance (Ohms)	51.43	56.24
Average Effective Er	4.24	3.73
Average Flight Time (pseconds)	832	784
Average Velocity (pseconds/inch)	174.5	163.7

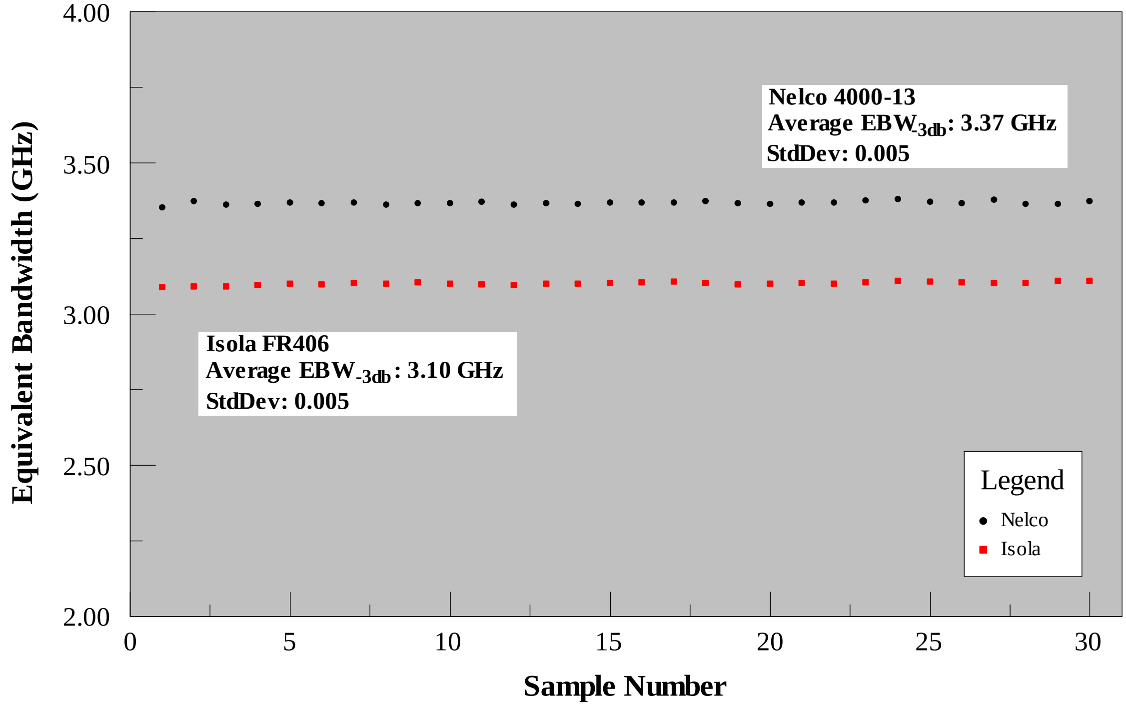

Figure 5 - Layer 3 Material Loss Comparison

Study 2 Loss Comparison by Line Length

Description

A study was done to compare the measurement of loss versus interconnect length. Five (5) interconnects of various lengths were measured. One measurement was taken on each interconnect and EBW_{-3db} was recorded/calculated.

This study was repeated on two (2) separate layers (Layer 1 and 7) on the two different materials.

Results

Table 9 - Loss vs. Line Length

Layer	Width (mil)	Length (inches)	Nelco EBW	Isola EBW
L1	5.75	1.00	4.739	5.115
L1	5.75	2.00	4.655	4.742
L1	5.75	4.50	3.421	3.085
L1	5.75	7.00	2.780	2.264
L1	5.75	12.00	1.522	1.161
L7	3.75	1.00	5.016	4.900
L7	3.75	2.00	4.766	4.574
L7	3.75	4.50	2.738	2.404
L7	3.75	7.00	1.622	1.573
L7	3.75	12.00	0.901	0.820

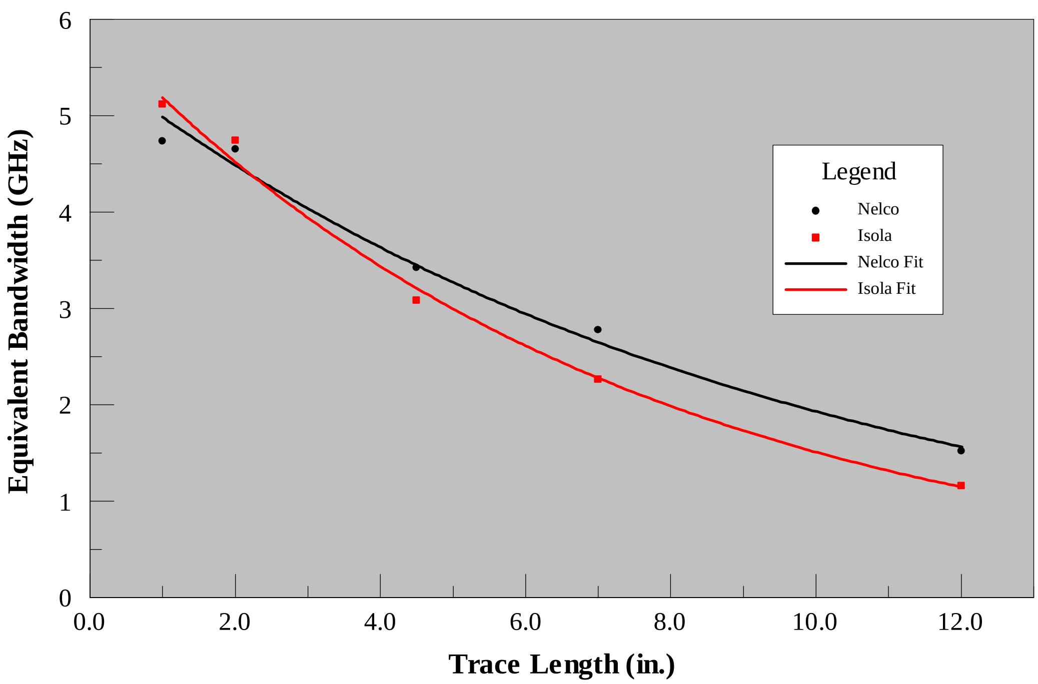

Figure 6 - Equivalent Bandwidth vs. Trace Length – Layer 1

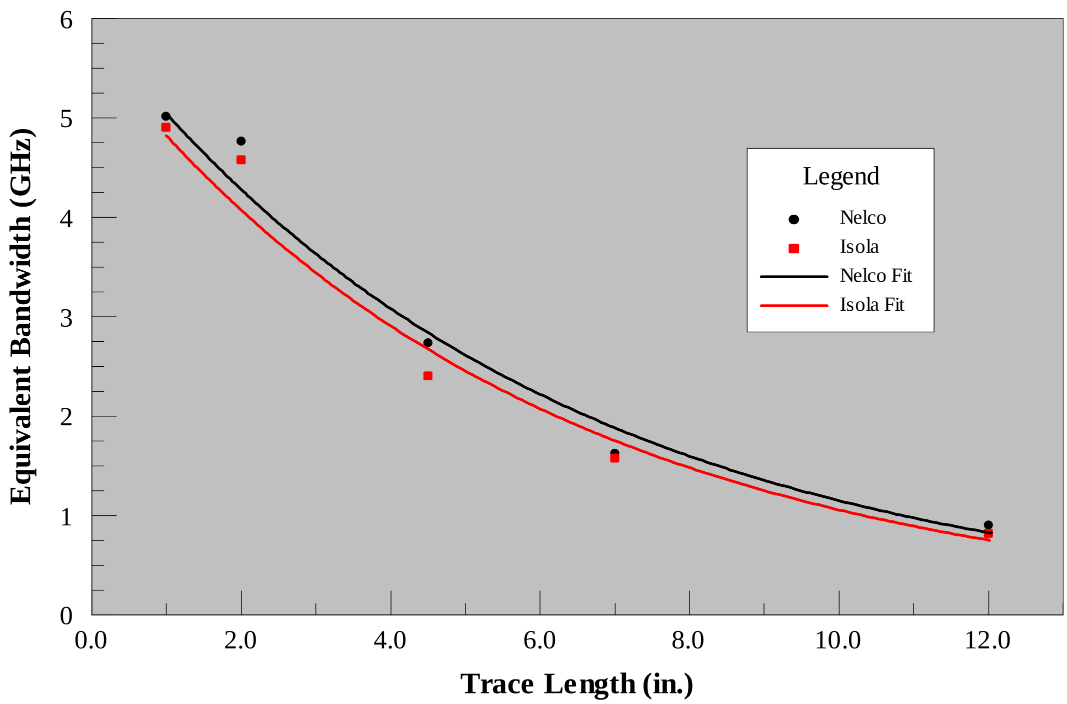

Figure 7 - Equivalent Bandwidth vs Trace Length – Layer 7

The results show that the Equivalent Bandwidth method of determining loss accurately predicts an increasing loss with increase in interconnect length. The anomaly at the shorter trace lengths in layer one will be addressed in follow-on investigations**.**

Study 3 Inter-Panel (Panel-to-Panel) Loss Variations

Description

A study was done to compare the measurement of loss from panel-to-panel. Four (4) panels of each material were selected. Each panel had three (3) interconnects of the same length at a 45 degree orientation on three-(3) separate layers. One measurement was taken on each interconnect and EBW_{-3db} was recorded/calculated

Results

Table 10 - Panel-to-Panel Variation Loss Data

Material	**Serial Number**	**Layer 1 Width: 7mil Len: 4.529”**	**Layer 3 Width: 6mil Len: 4.529”**	**Layer 9 Width: 6mil Len: 4.529”**
Nelco	SN#1	3.367	3.631	3.347
Nelco	SN#2	3.413	3.624	3.374
Nelco	SN#3	3.642	3.604	3.759
Nelco	SN#4	3.505	3.308	3.382
Isola	SN#1	2.955	3.046	3.174
Isola	SN#2	2.918	3.067	3.200
Isola	SN#3	2.982	2.985	3.118
Isola	SN#4	3.015	2.976	3.201

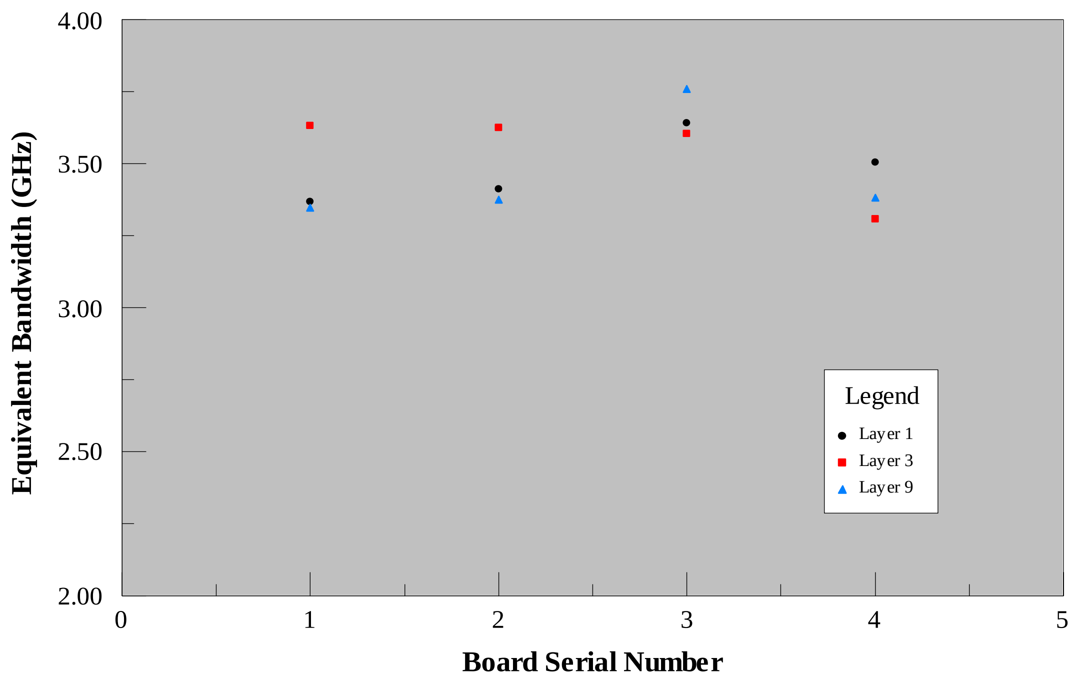

Figure 8 - Nelco Inter Panel Loss Variation

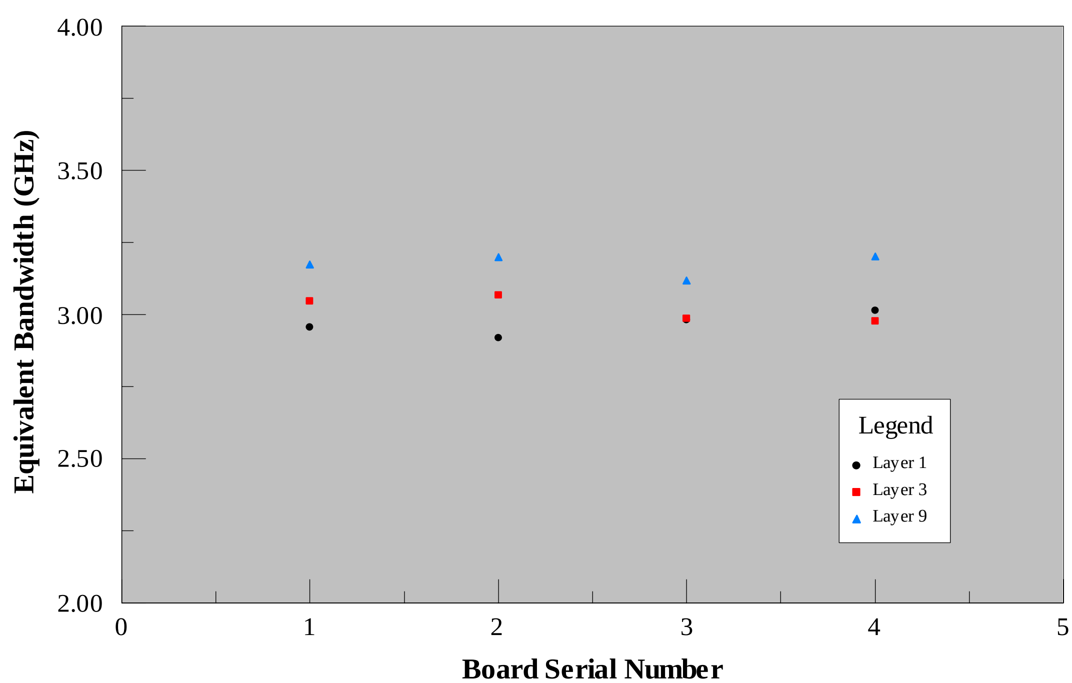

Figure 9 - Isola Inter Panel Loss Variation

The results indicate some variation in loss from panel to panel. The results indicate that the Equivalent Bandwidth method of determining loss has the required sensitivity to grade each production panel as to its loss characteristics.

Conclusions

For a TDR system with a fast rise time the Equivalent Bandwidth method of determining loss is a simple and effective method for use in a production environment. The method is also capable of determining loss differences among different materials. Based on experimental observations, smaller via sizes will improve the repeatability of the method and will extend the upper value of frequency that can be measured for an interconnect.

Further work is needed to evaluate the method with different materials, trace lengths, connecting structures, frequency ranges and the effect of different DUT impedances on the EBW_{-3db} measurement. Correlation with results obtained from other loss measurement techniques is also important.