

Production Measurement of Frequency Dependent Attenuation and Phase Constant of PCB Traces

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Abstract

As clock rates have increased and pulse widths have narrowed, signal loss at the higher frequencies has become a key problem for both designers and board fabricators. Current techniques for measuring signal loss during production testing of PCBs cannot directly provide the specific attenuation and phase shift for the trace being measured. A new measurement technique using short pulses has demonstrated in the laboratory that the propagation constant of a trace can be determined accurately and presented as attenuation and phase per unit length as functions of frequency to beyond 20 GHz. This Short Pulse Propagation measurement process has been evaluated as mature enough to transfer from a laboratory environment and become part of a mainstream production measurement system. The technique uses available sampling oscilloscopes, step generators, and hardware differentiators to obtain the high-frequency pulse needed for Time Domain Transmission (TDT) measurements. Since a production application of the Short Pulse Propagation process uses available equipment and proven measurement and mathematical techniques, it can provide an accurate and efficient tool for test, evaluation, and process control. The propagation constant that is obtained from the Short Pulse Propagation measurements also provides the foundational data for additional measurements and modeling to obtain the broadband dielectric constant and loss tangent on product-level, multi-layer PCB wiring.

Key Words: Short pulse propagation technique, causal broadband dielectric loss, production floor printed circuit board characterization

I. Introduction

Increasingly, the printed circuit board designer faces challenges associated with balancing the electrical performance requirements and the cost of any given packaging solution. Additionally, the manufacturer must have confidence that the product is meeting the customer's performance requirements throughout the production lifetime.

These challenges manifest themselves in a variety of areas. A particular area of importance is associated with the design of the transmission line within the printed circuit board. The electrical performance of the transmission line is influenced by a number of different parameters, including the dielectric properties of the laminate material, the copper trace cross section, the copper foil properties (resistivity and surface roughness), and any physical restrictions on the thickness of the board being designed. All of these parameters have manufacturing tolerances associated with them, which vary from one manufacturer to another.

Even as fundamental frequencies and spectral content increase, designers often seek the most cost effective solution which can deliver the expected electrical performance. As such, they find themselves often pushing any given transmission line design to the limit, perhaps working with lesser margin than would have been present in previous design efforts. Therefore, the ability to accurately predict the performance of any given design solution over a broad frequency range is paramount. Such understanding is necessary not only at the nominal design point, but also through the range driven by the real manufacturing tolerances. Some of these tolerances may not be known to the designer and therefore may present added risk.

A technique for accurately assessing the electrical performance of the manufactured printed circuit board on the production floor is therefore of increasing importance. In this paper, we discuss the operator friendly production implementation of the short-pulse propagation (SPP) test methodology, which is a time domain technique that provides

accurate broadband transmission line attenuation and phase constant information. Simple test structures are incorporated onto the board design and/or on panel coupons designed to reflect the functional trace parameters. The information garnered from these test structures can then be used to accept or reject product before shipping to the customer. This provides the customer with additional confidence in the shipped product. The information can furthermore be used as a basis to form highly accurate, causal broadband transmission line models as one applies the technique in the lab environment.

II. Background

The SPP test technique has been in use in the lab environment for well over a decade to characterize printed circuit board laminate materials and module package performance [1], [2]. The frequency to which one can obtain valid data is directly related to the equipment and test structure design.

The technique is described comprehensively in IPC TM650, section 2.5.5.12. Quite simply, two transmission structures of adequate similarity and uniformity, but different length, are assessed using commercially available time domain techniques. The launch structure and probe technique used must facilitate the required bandwidth of the final output. Depending on the DUT thickness, back drilling of the test structure PTHs may be necessary to ensure adequate bandwidth.

Similarity is assured through Time Domain Reflectometry (TDR) analysis, whereby the TDR responses of the long and short transmission lines are compared and evaluated for similarity. Upon determination that the DUT is suitable, the step source of a sampling oscilloscope is differentiated and launched into the transmission line structure. The differentiation is performed using a passive impulse forming network to avoid irregularities and/or inconsistencies resulting from software differentiation. The resulting waveform is then digitized and saved for further processing. This is repeated on a second structure. Typically, traces of 3cm and 10cm lengths are used.

The waveforms are subsequently processed to ensure they are referenced properly and end effects are filtered out, removing undesirable reflections and eliminating the need for de-embedding structures and routines. After these preparatory steps, the data is Fourier transformed and a ratio of the data results in $\alpha(f)$, the attenuation coefficient, and $\beta(f)$, the phase constant.

The aforementioned process forms the basis for a production level tester capable of providing $\alpha(f)$ and $\beta(f)$. In Fig. 1 we see example coupon design data, while Fig. 2 portrays actual production board SPP coupons as implemented. Additional structures are included beyond the two basic transmission lines to facilitate more comprehensive analysis, if needed. The structures' orientation may be modified to take up less physical space, as required.

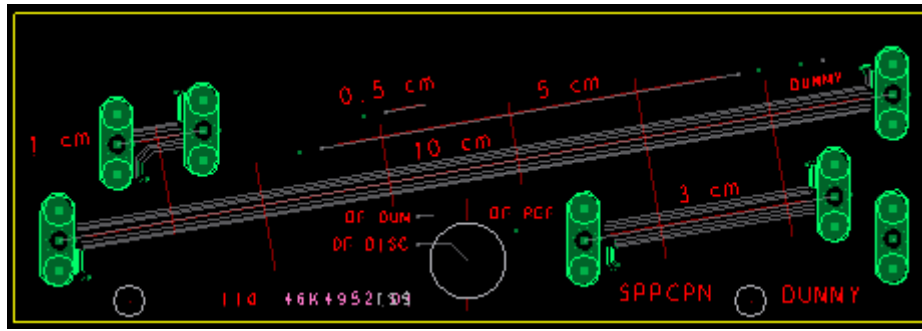


Fig. 1 Example SPP production test structure, design data

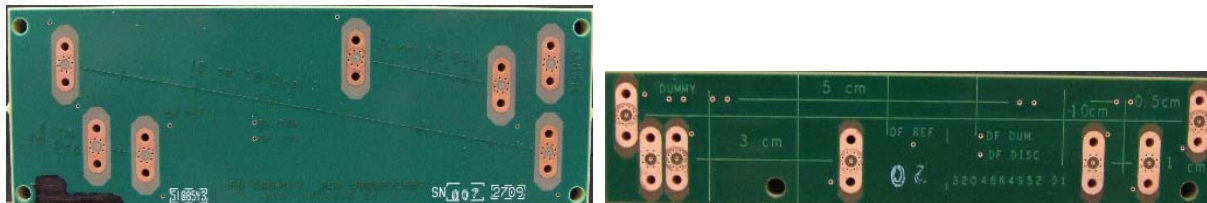


Fig. 2 Actual production test coupons

Fig. 3 provides a sample set of impulse waveforms as taken on a production test coupon in a lab setting. Upon processing of the data taken on a number of product coupons over three suppliers, we observe the resulting comparative $\alpha(f)$ data seen in Fig. 4. This particular data was generated on a production board using test structures as seen in Figure 1. The board is approximately 5.1mm (0.200") thick. The signal launch PTHs were back drilled to facilitate bandwidth up to approximately 20GHz.

The resulting fitted $\alpha(f)$ data shown in Fig. 4 may then be compared against specified values within the frequency range of interest to ensure the part meets the customer's requirements. In Table 1, we observe this data at discrete frequencies, and compare the relative performance of the suppliers. One observes the performance difference driven by the supplier's processes, even though the input specifications were the same at each supplier. In this particular case, the delta was driven in large part by skin effects as a result of the Cu roughness as output

by the various adhesion promotion treatment processes used at each supplier.

Table 1. Relative transmission line performance, averaged over a number of production samples

Frequency, GHz	Supplier 1, Attenuation, % Delta To Supplier 3	Supplier 2, Attenuation, % Delta To Supplier 3
3	0.9	9.9
6	3.2	15.2
10	7.4	18.2
15	8.2	19.6
20	9.4	20.2

Outside of the production environment, one can extend the use of the $\alpha(f)$ and $\beta(f)$ data generated in this fashion and extract the causal broadband effective dielectric constant and loss tangent. This facilitates the generation of accurate transmission line models which can then be used for system simulation exercises.

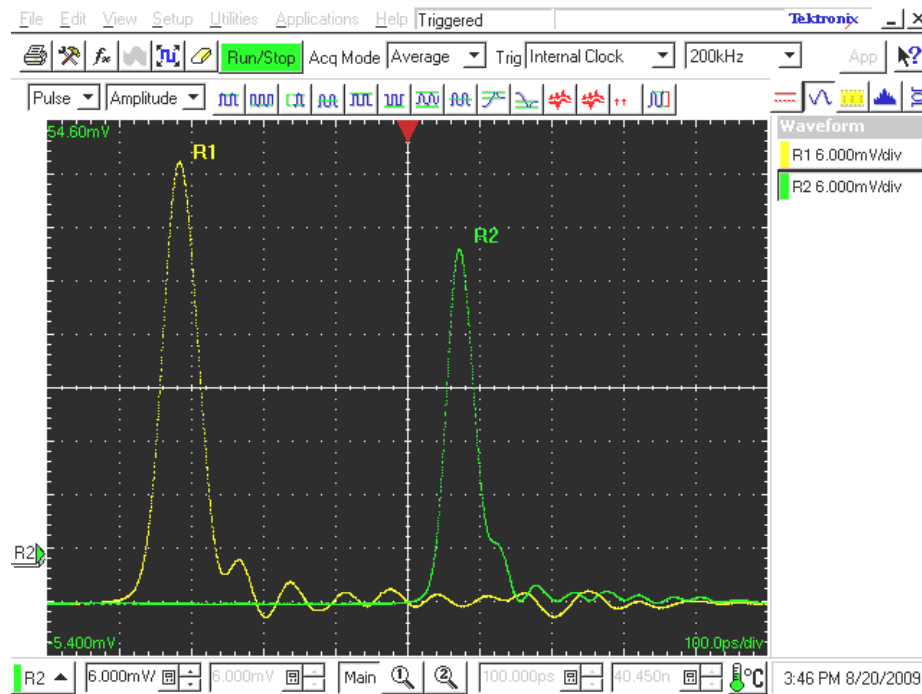


Fig. 3 Example SPP impulse response on 3cm (R1) and 10cm (R2) transmission lines

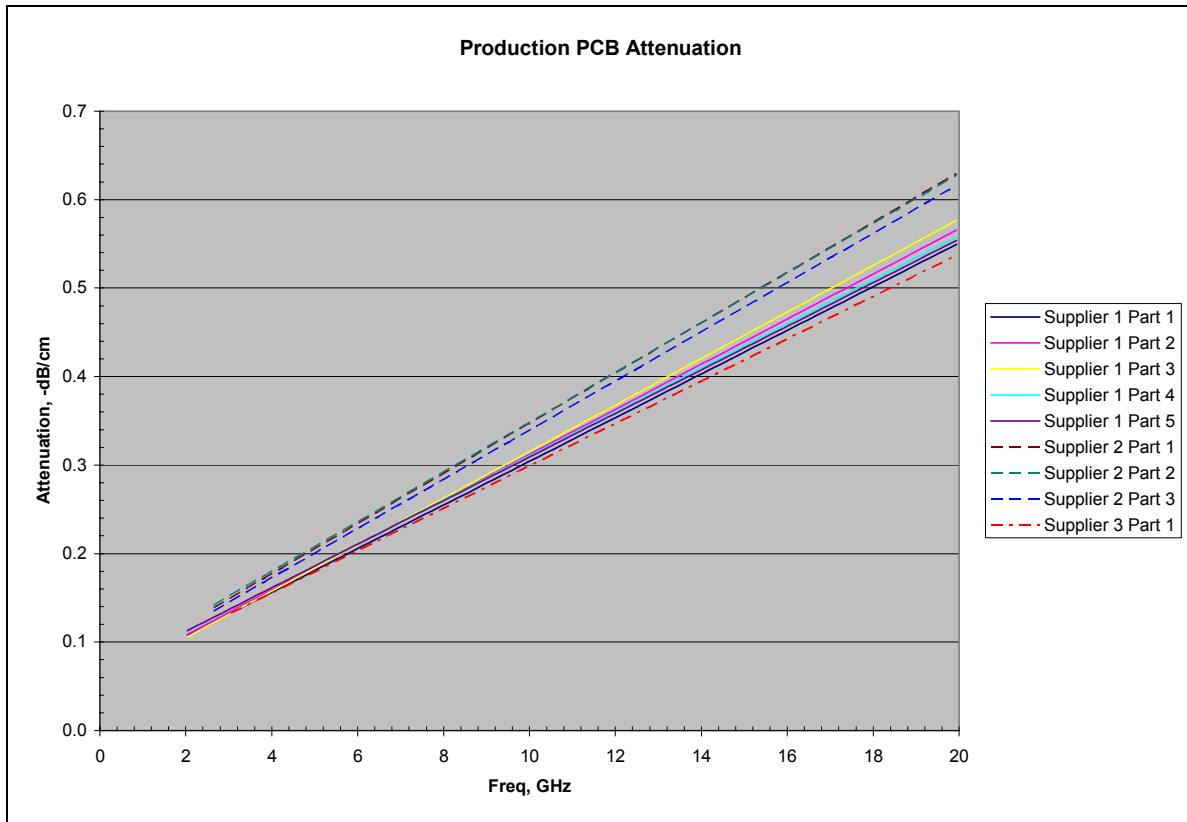


Fig. 4 Example resultant $\alpha(f)$ output across three PCB suppliers, -dB/cm vs. Frequency

III. Bringing SPP Into The Production Environment

To transform the SPP process from a laboratory process to a mainstream production process requires developing an SPP Production System that includes all the necessary capabilities that allow it to be part of a larger production process. These capabilities include the administrative and infrastructure functions to interface with a company's production management systems to obtain test specifications, maintain job control, store the acquired test data, and to analyze and report the results. From a more technical standpoint it requires streamlining laboratory procedures for performing the measurements, developing software to automatically control the test equipment, modifying test equipment to support the automated approach, and identifying and encapsulating the knowledge gained in the laboratory into the system to provide accurate and repeatable results.

There are many challenges in transforming a laboratory process to a stable and accurate production system. The most difficult challenges are those involving human interpretation. In the SPP laboratory process some of the critical human

decision areas include determining the degree of similarity of the long and short traces, the windowing of the short and long pulses prior to the Fourier transformation, and the assessment of the attenuation and phase results. On the other hand, automating a laboratory process can greatly improve many time consuming and potentially inaccurate laboratory activities such as setting oscilloscope values; downloading, formatting, naming, storing and presenting oscilloscope data; and obtaining consistent and accurate measurements over a wide range of operators.

Early in the design process for the SPP Production System the decision was made to implement it as added functionality to the already existing ACCU-Prober production Time Domain Reflectometry (TDR) system. This system provides completely automated oscilloscope control, data acquisition, data assessment and storage, job control, and manually controlled, non-robotic probing. Many of the existing subsystems such as operating in a production environment, automated oscilloscope control, database storage, job control processes, and user interfaces can be easily modified to create additional SPP modules with similar basic functions.

The existing design approach that allows extensibility to a robotic probing solution as production requirements increase is being implemented also in the SPP Production System.

The SPP TDR screening functions are similar enough to those in the existing production TDR system that only minimal software changes have been needed. The existing SQL Server database and data import and retrieval functions have been expanded to support the SPP requirements. In some cases no changes were required to database tables such as those storing user, customer, and operator data. In other cases some tables required additional columns to be added. For the SPP unique items new database tables and relationships were developed. This leveraging of many portions of an existing production system provided a robust functioning process early in the development of the SPP Production System, and allowed the main efforts of the SPP Production System development to be focused on the unique technical aspects of the SPP process.

The two data acquisition aspects of the SPP process most different from the existing production process are the probing methods and the fact that SPP performs both TDR measurements and Time Domain Transmission (TDT) measurements of short pulses while the existing process performs only TDR measurements. The signal processing aspects of the SPP process most different from the ACCU-Prober process are the windowing of the acquired short pulses to remove reflections, Fourier transformation, and ratioing of the Fourier transforms of the short and long traces.

IV. SPP Production Probing

One robust laboratory probing approach uses a Molex connector bolted to the connection point. Bolting the Molex probe to the test boards is a good data acquisition solution, but it is too time-consuming for a production system. Previous laboratory investigations assessed the use of set screws in the screw holes on the bottom of the Molex probe to guide manual placement of it on the DUT, while still using fixtures after the probe is placed. Assessment of this technique during the production system development showed there was still a relatively large misalignment of the probe once placed because of the small diameter of the set screws. Also, the set screws could not be tightened against any surface and would slowly advance or retreat in the screw holes with repeated probe placements. A variation of the set screw approach

was developed. Button head screws were machined so the diameter of the head was only a minimal amount less than the diameter of the DUT connection holes (Fig. 5). These modified button head screws could be tightened against the base of the Molex probe, and they provided very minimal misalignment once placed on the DUT contact point.



Fig. 5 Close up of probe with button head guide screws

After probe placement, vertical alignment and the proper amount of force pressing the probe to the board are still required for an acceptable connection. To reduce the time required to place the probes on the DUT, a Probing Station with articulated arms has been designed. The articulation of the horizontal arms shown in Fig. 6 can be modulated to provide easy bending for positioning of the probes. Then the arms can be made quite rigid to maintain the position. The vertical arm near the probe is incrementally adjustable to provide the required down force. The Probing Station shown in Fig. 6 is large enough to handle coupons and panels.

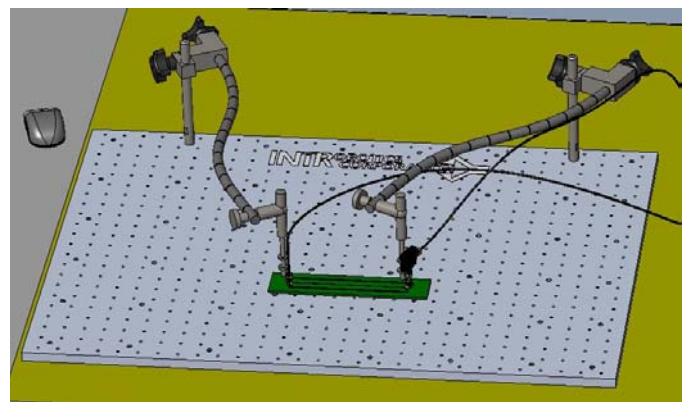


Fig. 6 Production SPP Probing Station

V. SPP Production TDR Similarity Assessment

The SPP process requires that the short and long traces be very similar. Four TDR measurements are used to determine the similarity: long forward, short forward, long backward, short backward. The SPP Production System performs all four measurements automatically, guiding the operator to place the probe for each measurement. Once the probe is placed, the operator actuates a foot pedal to start the measurement process. The technical aspects of controlling the scope over Ethernet, determining scope settings from test specifications and trace lengths, making the appropriate measurements, and downloading and storing the data and waveforms were developed several years ago. The main changes for SPP were implementing the software flow for measuring the long forward trace first, and then maintaining the scope settings while performing the other three TDR measurements. Where ACCU-

Prober makes one TDR measurement and presents the results to the operator, the SPP Production System performs four TDR measurements and presents the results to the operator in a compact presentation. Fig. 7 shows the Production SPP TDR Testing screen when the system has completed the TDR measurements on one Trace Set and is halfway through the measurements on a second. Note how each of the four TDR measurement results are presented separated by commas as in the "Mean Z" column. Also note the guidance to the operator at the bottom center of the screen. If a particular Trace Set fails to meet the TDR measurement criteria that have been established, a clear indication is provided on the display grid that the Trace Set has not passed the TDR screening. Fig. 8 shows a representative set of four TDR waveforms from stored test data that was downloaded automatically from the scope.

Job Information

Job Number: Job SPP 002
 Customer: Acme Boards
 ICN: ICN SPP 001
 Date Code: 081909
 Current DUT Serial Number: 2

☐ Use Date and Time

Test Point Information

Single-ended Points: 2
 Number of Boards Tested This Session: 0

Calibration Information

CH 1 P Single-ended Cal Date: 8/13/2009

Current Step Specs

Line Pair Being Tested: 1
 Z NonUniformity: 20.00
 Z Difference: 5.00

Current DUT Progress
All Pass

Job Summary
All Pass
Click for Detail

Show Waveforms

Step Number	Trace Set Name	Diff	Short Trace Node Name	Long Trace Node Name	Z Non Uniformity (%)	Mean Z (Ohms)	Z Difference (%)
					LF, SF, LB, SB	LF, SF, LB, SB	F, B
1	Trace Set 01	☐	Short Node 01	Long Node 01	4.7, 7.6, 7, 10.7	50.4, 50.8, 49.7, 50.2	0.8, 0.9
2	Trace Set 02	☐	Short Node 02	Long Node 02	4.3, 8.4, .	50, 50.4, .	0.8
		☐					
*		☐					

LF = Long Fwd
 SF = Short Fwd
 LB = Long Bwd
 SB = Short Bwd
 F = Fwd
 B = Bwd

Cancel Testing
Delete Test Data for the Serial Number

Long Line Backward
Place the Probe on the Test Point And Press the Foot Pedal Or Click the Take Measurement Button

Take Measurement

Stop Testing Resume Later

Fig. 7 Production SPP TDR Testing Screen

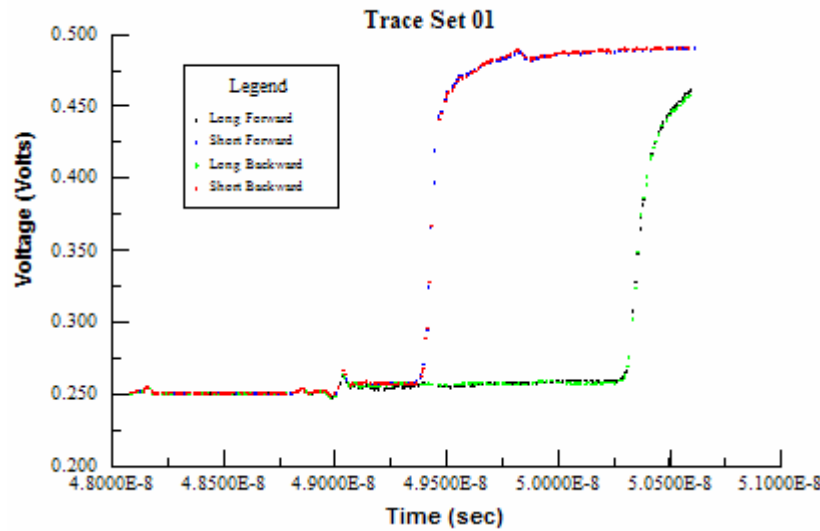


Fig. 8 Production SPP TDR Data

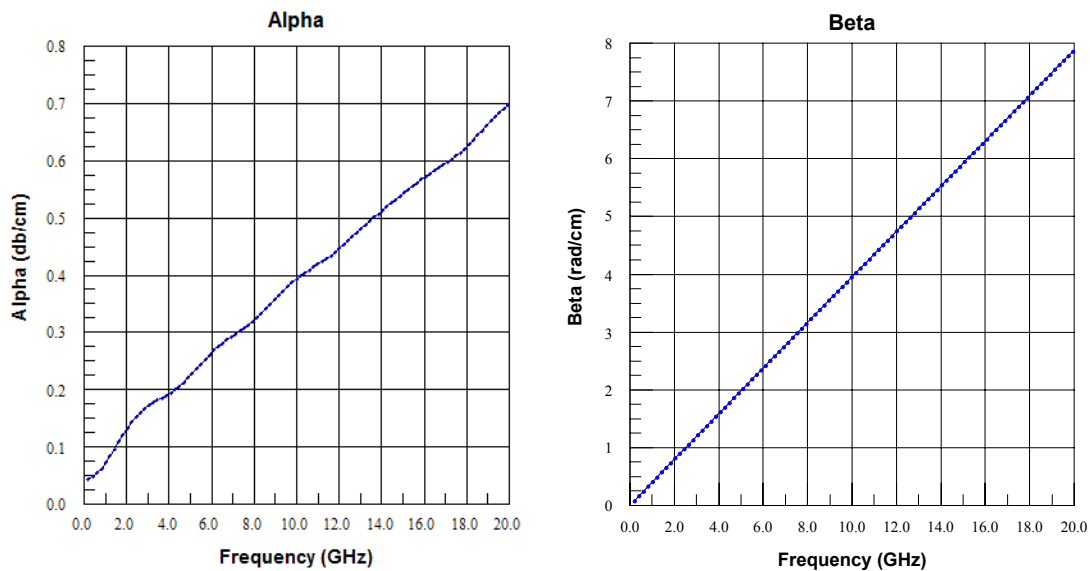


Fig. 9 Production SPP Output Plots of Alpha and Beta

VI. SPP Production TDT Measurements

SPP TDT measurements can be performed on the Trace Sets that have passed the TDR screening. The Picosecond Pulse Labs' (PSPL) 5208 Impulse Forming Network (IFN) and a Molex connector probe are connected to the scope channel propagating the step pulse. Cables and a Molex probe are connected to the channel receiving the signal. The operator will be guided through the TDT measurements in a manner similar to that used for the TDR measurements. The software will determine the proper scope settings based on the trace lengths, and

the scope will automatically perform the short pulse measurements after the operator presses the foot pedal. The data and waveforms will be saved automatically to the database after the pulses are measured.

VII. SPP Production Short Pulse Signal Processing

Immediately after the data has been saved, the software will perform the computations to prepare the pulses for the Fourier transformations, perform the transformations, determine the alpha and beta

values as functions of frequency (Fig. 9), and perform an assessment of the frequency range over which the results are valid. Embedded software tools from National Instruments are being used for performing the Fourier Transforms. The transform operations and alpha and beta computations have been programmed. Results have been compared with the results obtained from IBM's Gamma-Z software and other transform software and are identical within accepted engineering tolerances for identical inputs. If a trace set does not meet the established criteria, a clear indication will be displayed on the interface that the Trace Set has not passed the TDT process.

Additional software modules are being developed to perform the pulse level shifting and windowing, the alpha and beta assessments, and waveform display. Once completed, end-to-end testing will begin. As that is completed, the first production units will be available for deployment.

VIII. Conclusion

It has been shown that, using a straightforward time domain technique, one is able to ascertain detailed broadband $\alpha(f)$ and $\beta(f)$ characteristics from test structures embedded within the actual production PCB panel. These characteristics, which may vary driven by numerous manufacturing tolerances, can be used to determine the acceptability of the production part. With minimal additional processing, these production structures are capable of yielding valid data up to 20GHz. This bandwidth may be extended with suitable test equipment and probe design.

The process and equipment used with this technique is being adapted for use on the manufacturing floor as an augmentation to an existing test suite. The data acquisition is facilitated by a robust probe solution. Data is automatically processed using commercially available software tools as well as software modules which are currently being developed.

This production assessment technique will enable the card developer to have added confidence in the design, as well as providing the PCB fabricator with the tools necessary to meet the customer requirements.

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