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Characterization Methodology for High Density Microwave Fixtures

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Abstract

This paper presents the characterization of a PCI-express test fixture that was created to passively probe a x16 link on a PCB. This fixture plugs into the 48-pin, midbus footprint which has been adopted by as the industry standard for observing PCI-express links on a PCB. This fixture is used to observe signals and pass them to a piece of test equipment (TDR, VNA, or oscilloscope). Engineers reading this paper will be exposed to how a Microwave test fixture with a high density interconnect was designed, measured, and modeled which ultimately resulted in the performance specifications of the fixture.

Author(s) Biography

Dr. Brock J. LaMeres received his BSEE from Montana State University in 1998 and his MSEE and Ph.D. from the University of Colorado in 2001 and 2005 respectively. He is currently an assistant professor in the Electrical and Computer Department at Montana State University, Bozeman. LaMeres is the co-founder of *Probing Technology, Inc*, a company which specializes in the design of high performance probing interconnect systems for use in Test and Measurement. LaMeres' research and teaching interests are in the area of high speed digital system design and digital signal processing using FPGA's. Prior to joining MSU, LaMeres was an R&D engineer at Agilent Technologies for 8 years where he designed acquisition and probing systems for Logic Analyzers. LaMeres has published over 40 papers in the area of high speed signal propagation and has been granted 9 US patents in the area of electronic probing interconnect.

Brent A. Holcombe received his BSME from the University of Washington in 1996. Holcombe is also the co-founder of *Probing Technology, Inc*, a company which specializes in the design of high performance probing interconnect systems for use in Test and Measurement. Prior to joining Probing Technology, Holcombe was an R&D engineer at Hewlett-Packard and Agilent Technologies for 10 years where he designed interconnect and probing solutions for Logic Analyzers and Oscilloscopes. Holcombe has published 3 papers in the area of high speed interconnect solutions and has been granted 16 US patents in the area of electronic and mechanical probing interconnect.

Emad Soubh Holds 2 BS one in Mechanical engineering and the second in Plastic engineering, also received his MBA from WA. State University 1996. Emad has been in the field of high speed interconnects filed, specifically in the Test and Measurements Industry, for 17 years, and holds 14 patents in that filed. Emad Holds the position of High speed cable Technology manager at Samtec. Inc. for the last 4 years. Prior to Samtec Emad held the position of Technical Lead at Precision Interconnect/Tyco for 13 years.

1. Introduction

The move toward multi-Gigabit serial links for inter-chip communication has forced digital system engineers to adopt microwave design principles in order to reliably transmit information. Designers who used to worry about terminations, cross-talk, and skew are now concerned about such factors as jitter, insertion loss, and bit error rates. This paradigm shift in design methodology has been successfully undertaken in high-end system designs such as network switches and servers over the past 5 years. Today we are beginning to see multi-Gigabit link technology appear in the more mainstream electronics market. As this technology makes its way into the everyday lives of engineers, we are seeing the basic interconnect need for turning on and testing these designs becoming a difficult challenge.

Test fixtures have always played a critical role in semiconductor turn-on and system level debug. *Test fixtures* are the custom printed circuit board (PCB) assemblies that are created to stimulate and observe signals coming into and out of a device under test (DUT). These fixtures are typically created for internal use and provide the basic connectivity of the DUT to whatever test equipment or turn-on environment is being used. Since the test fixtures are for internal use, they can provide a superset of functionality that will not be deployed in the final production design. This allows fixtures to contain higher channel counts for additional functionality. This typically requires the fixture to contain high density connector schemes.

The design of these fixtures has become a difficult problem for the general engineering community as signal frequencies move into the Gigahertz arena. The need for fixturing is still present but now they need to be designed with microwave precision and care. This problem becomes even worse as high channel counts and high density connectors are required.

One of the challenges of microwave fixturing is characterizing its performance so that the fixture's impact on the signals coming to and from the DUT is understood. If the performance of the fixture is characterized, then it can be de-embedded form the results observed by the test system and only the performance of the DUT can be obtained.

This paper presents the characterization of a PCI-express test fixture that was created to passively probe a x16 link as it traverses a printed circuit board (PCB). This fixture plugs into the 48-pin, midbus footprint which has been adopted by as the industry standard for observing PCI-express links on a PCB. The fixture contains a high density LGA-style interconnect that makes contact to the PCB footprint. High density interconnect is now being deployed in multi-Gigabit links due to the high channel count requirements. Off-PCB, microwave interconnect has historically been made using connectors such as SMA, N-type, or SMP. High density connectors have not traditionally been used for microwave signals due to their lack of impedance control and excess parasitics. However, new high density connectors are being fabricated with extremely small size which enables them to transmit microwave signals without severely degrading the signal quality. This type of connection needs to be carefully characterized to guarantee performance. In addition to the high density connection, this fixture contains PCB traces and traditional microwave SMP connectors which are used to get signals from the fixture into a coaxial cable. This fixture is used to probe signals on a PCI-express link and pass them to a piece of test equipment (TDR, VNA, or oscilloscope).

This paper will describe the fixture characterization process which involved measurement and equivalent SPICE model generation. The measurement data was collected using an 18GHz Tektronix TDR oscilloscope. The TDR oscilloscope was used to stimulate different ports of the fixture and the corresponding TDR and TDT results were obtained. This paper describes how selectively stimulating ports on the fixture enable the extraction of quantities such as Near-End and Far-End X-talk, Single-Ended and Differential Impedance, and Frequency Dependant Loss. The paper also describes how the measurement data was taken into a SPICE simulator and an equivalent circuit model of the TDR step and the passive fixture is created. Once created, this model was used under different stimulus types in order to predict the input impedance, insertion loss, and step response to different risetimes. A correlated SPICE model for a fixture is of great interest to engineers because it can be incorporated into system level simulation to better match measurement results. Once system level measurements are correlated to simulations, the fixture model can be de-embedded from the simulation to see the behavior of the original system.

Engineers reading this paper and attending this presentation will be exposed to how a microwave test fixture with a high density interconnect was designed, measured, and modeled which ultimately resulted in the performance specifications of this fixture. They will also be exposed to the application of a microwave fixture to a probing application, which can provide connectivity for TDR's, VNA's, and oscilloscopes.

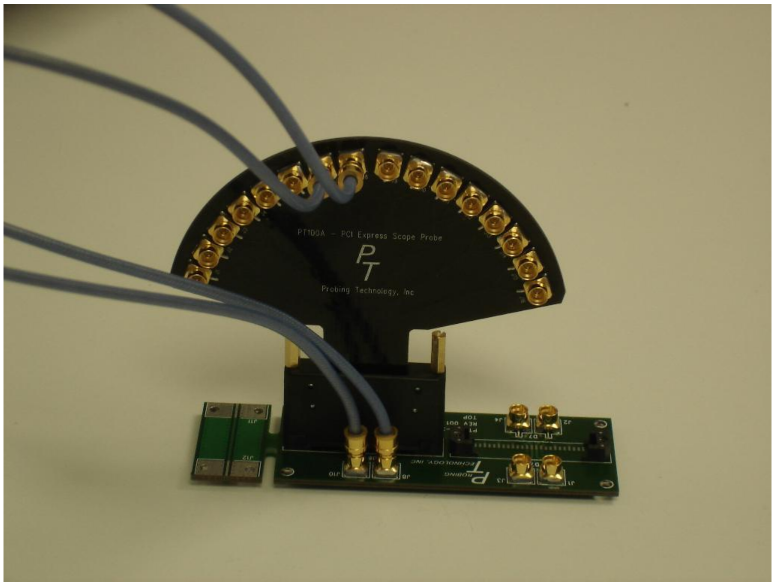


Figure 1. PCI-Express Fixture for Passively Probing a x16 Link

2. Fixture Design

A probing fixture was designed by *Probing Technologies, Inc* to bring signals from a PCI-express, x16, midbus footprint out to general purpose SMA connectors. This fixture can be used to passively probe signals on a PCI-express link using a 7:1 resistive divider configuration. This configuration is well suited for parametric testing of the link using a real-time or sampling oscilloscope. Eye diagrams, jitter tolerance, and attenuation can be observed in real-time to verify that the transceivers are operating within the PCI-express specifications. The resistive divider configuration (PT100-DC) uses a high density custom, LGA interconnect from *Samtec, Inc* called SPIRIT^{TM} to interface the fixture PCB to the midbus footprint. The fixture PCB contains 300ohm resistors, followed by 50ohm transmission lines to bring the signals to high speed SMP connectors. A 12" SMP-to-SMA coaxial cable is then used to connect the fixture to test equipment. The transmission lines on the fixture PCB were designed to have 50 ohm, single-ended impedance and to form a loosely coupled 100ohm differential transmission line. NELCO-13-SI was used as the dielectric for the 4-layer, PCB.

The fixture can also be configured as a straight 50ohm pass through system (PT100-TDR). This configuration is ideal for applications where a user wants to drive high speed links directly into our out of an instrument in order to perform parametric testing or impedance analysis. This configuration is ideal for connecting a TDR oscilloscope, a VNA, or a high-speed signal generator to the IC's on the system PCB.

3. Modeling Approach

One of the challenges of designing a microwave fixture is analyzing its performance. While each component used in the fixture has ideal specifications associated with it, the performance of the entire assembled system will vary depending on how the PCB stackup, pads, and routing are accomplished. In order to evaluate the performance of the entire system in addition to each individual component, an equivalent SPICE model is constructed. This is accomplished by stimulating the fixture with a known source and then observing the fixtures outputs. By varying the locations of the stimulus and observation points, individual signal paths can be characterized.

The characterization approach taken in this project uses Time Domain Reflectrometry (TDR) to stimulate the fixture and then observe reflections (TDR) and transmissions (TDT) of the fixture. The results of each measurement are brought into a SPICE simulation environment and then an equivalent model is created that matches the measurement results. This approach is based on linear system theory where a given stimulus $x(t)$ produces an output $y(t)$ when connected to a system with a transfer function $h(t)$. In the time domain, this relationship is defined as:

$$y(t) = h(t) * x(t)$$

where * is the convolution operator. This simple expression says that if we know the input function *x(t)*, (i.e., the step output of the TDR oscilloscope) and we find the output of the system *y(t)*, (i.e., the measurement observed on the TDR oscilloscope), we can solve for the transfer function of the system *h(t)*.

One of the advantages of this type of linear systems approach is that the expression can be transformed into the frequency domain to give a different view of the results. Since the convolution operator in the time domain transforms into a multiplication operator in the frequency domain, the expression becomes:

$$Y(s) = H(s) \cdot X(s)$$

This transformation indicates that the characteristics of the system being measured can be obtained in either the time or frequency domain. In addition, the results in one domain can be transformed into results in the other domain. This also illustrates that there are two different approaches to modeling a microwave fixture. The first is in the time domain using TDR/TDT and the second is in the frequency domain using a Vector Network Analyzer (VNA). However, both methods will produce the same result.

One advantage of the time domain is that it produces initial results that are more easily interpreted with regards to location on the fixture. This allows an intuitive glance into which components on the fixture are causing reflections, loss, or resonances.

There are many software packages that exist that will automatically take the results from a TDR or VNA measurement and create an equivalent SPICE model or S-parameter data for you. While these packages produce correct results, they often do not give the engineering performing the characterization an intuitive feel for where the loss is coming from. The approach in this project is more manual in nature, but results in a model that can be easily interpreted for how each individual piece of the system performs when integrated together.

4. Characterization Results

4.1 Test Setup

The characterization in this project was accomplished using a *Tektronix DSA8200 Digital Serial Analyzer Sampling Oscilloscope* with an 80E04 Differential TDR Plug-In Module. This setup allows a stimulus step voltage with a rise time of 18ps and an observation bandwidth of 20GHz. The results of the measurements were brought into the *Agilent Advanced Design System (ADS) Environment* where they could be viewed and compared to a SPICE simulation model.

The results of the oscilloscope measurements were first exported to a CSV file that contained time and voltage information about the waveform displayed on the oscilloscope screen. This file was then converted into a *TIM* format that is used by *ADS*. *ADS* can import a *TIM* file into a dataset. Once the data is in a dataset within *ADS*, the information can be used for viewing or as a voltage source component.

Figure 2. Test Setup

4.2 DUT Fixture Design

The first step in characterizing a fixture is to connect the Device-Under-Test (DUT) to the test equipment. This requires the development of *another* custom test fixture (i.e., a DUT Fixture) that allows signals to be injected to the probe fixture (DUT). For this project, a simple 4-layer DUT fixture was created that allows signals to be injected into the probe fixture in a variety of configurations. Two PCI Express midbus footprints were put on the DUT fixture. The first footprint allowed a differential pair to pass directly through the footprint. This allowed the characterization of the probe fixture when configured as a *Shunt* load. The second footprint allowed signals to be driven directly into the probe fixture in order to view it as an *In-Line* load.

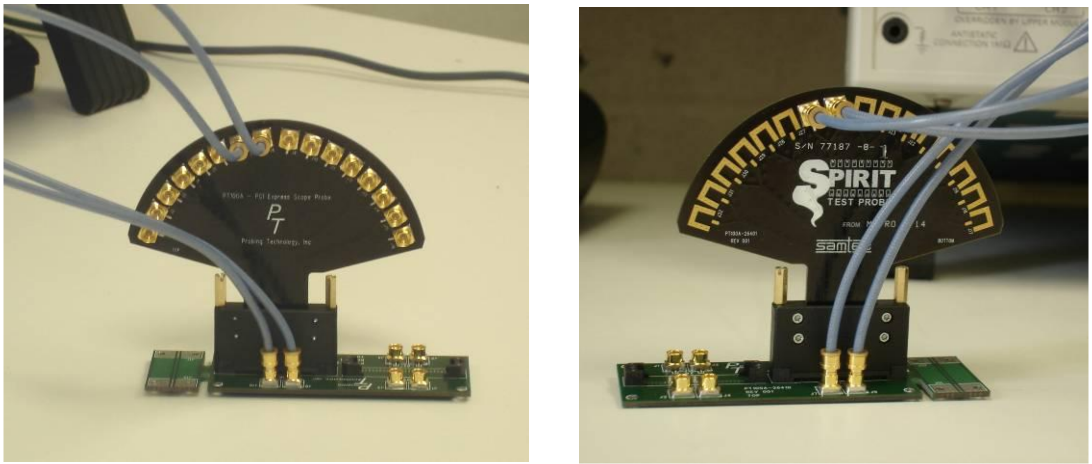


Figure 3. DUT Fixture Setup

We ultimately want to develop an equivalent model of only the DUT. However, since we have inserted an additional DUT fixture into the measurement, this will affect our results. In order to remove the effect of the DUT fixture, we first build an equivalent model of only the DUT fixture. Then in the final model, we can remove the portion of the SPICE deck that describes the DUT fixture, leaving only the model for our probe. This is called *de-embedding*. Once again, there are many software packages that will perform this de-embedding for you. However, they often do not give an intuitive feel for where the loss is coming from.

4.3 Stimulus Model

We want to build an equivalent SPICE model that represents the performance of our fixture. The equivalent SPICE model should produce the same results *y(t)* when stimulated with the same input forcing function *x(t)*. This requires us to build an equivalent forcing function model in SPICE that is identical to the forcing function being created by the TDR oscilloscope. This is one of the most crucial parts of modeling because any imperfections in the stimulus function will create unexpected results. While the unexpected results are accurate, they may not be of concern in the final use of the fixture.

The TDR output step voltage has imperfections on it that must be modeled. The simplest way to accomplish this is to simply take a measurement of *only* the TDR step and then import the waveform into the SPICE simulator and use the data as a voltage source. This allows the SPICE simulation to use the exact forcing function as used in the real measurement setup.

4.4 Coaxial Cable Model

The next step in building the model is to build an equivalent circuit for the cables. One shortcut that can be taken to de-embed the coaxial cables of the test equipment is to include their loss in the stimulus model created above. In this project, the same cables that are used between the test equipment and the DUT fixture are also used on the backend of the fixture. As a result, if a model can be created initially for the test equipment cables, that model can be used in two locations.

Coaxial cable loss typically has three loss components. The first is simply DC loss in the center conductor. This loss is typically neglected for larger cables, however it can become in the magnitudes of several ohms when using very fine gauge coax or very long cables. The 2nd and 3rd sources of loss in the cable are frequency dependent and come in the form of dielectric loss and skin effect loss. Both of these losses increase with frequency and can be difficult to model in the time domain due to their multiple-pole roll-off behavior.

For this project, a 12”, 18 GHz, Cable with negligible DC loss was used. The frequency dependant loss was modeled using an RC ladder network that allows poles of different magnitudes to be switched in at different frequencies. For the 12” cable used in this project, 3 RC ladders were sufficient to model the behavior out to 18GHz.

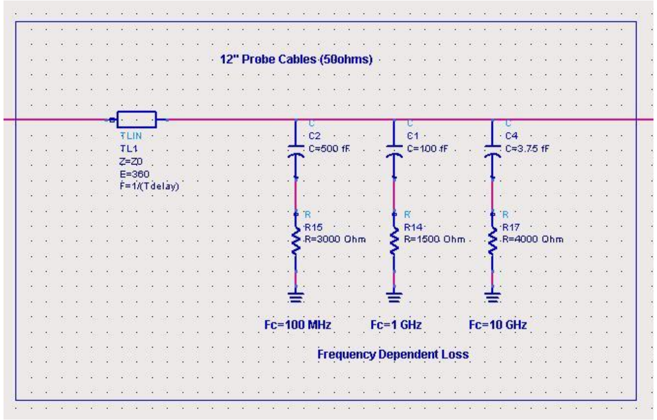


Figure 4. Coaxial Cable Model

4.5 DUT Fixture Model

Now that the stimulus and the coaxial cables are modeled, the DUT fixture model can be created. In this project, SMP connectors were used to connect the Coaxial cables to the DUT fixture PCB. The model created for the coaxial-to-SMP launch can be also used for the coaxial-to-SMP transition on the probe fixture itself.

4.6 PT100-TDR In-Line Probe Fixture Model

Now the test system has been completely modeled, the probe fixture can be attached. The first configuration that was tested is the straight 50-ohm pass-through version (PT100-TDR). This configuration allows a more intuitive view of each component in the probe since the system is ideally 50ohms throughout. Any impedance variance from 50ohms can be easily identified spatially on the fixture using the delay time from the source in the TDR measurement.

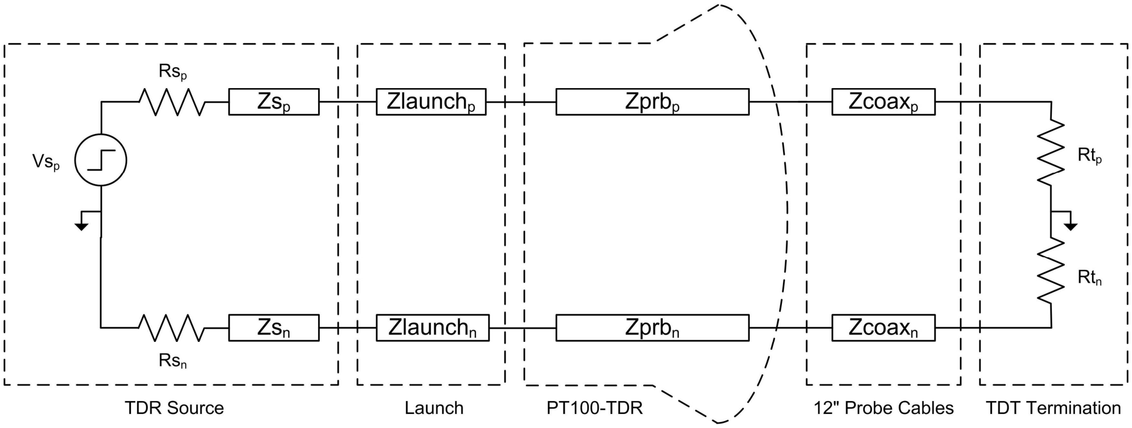
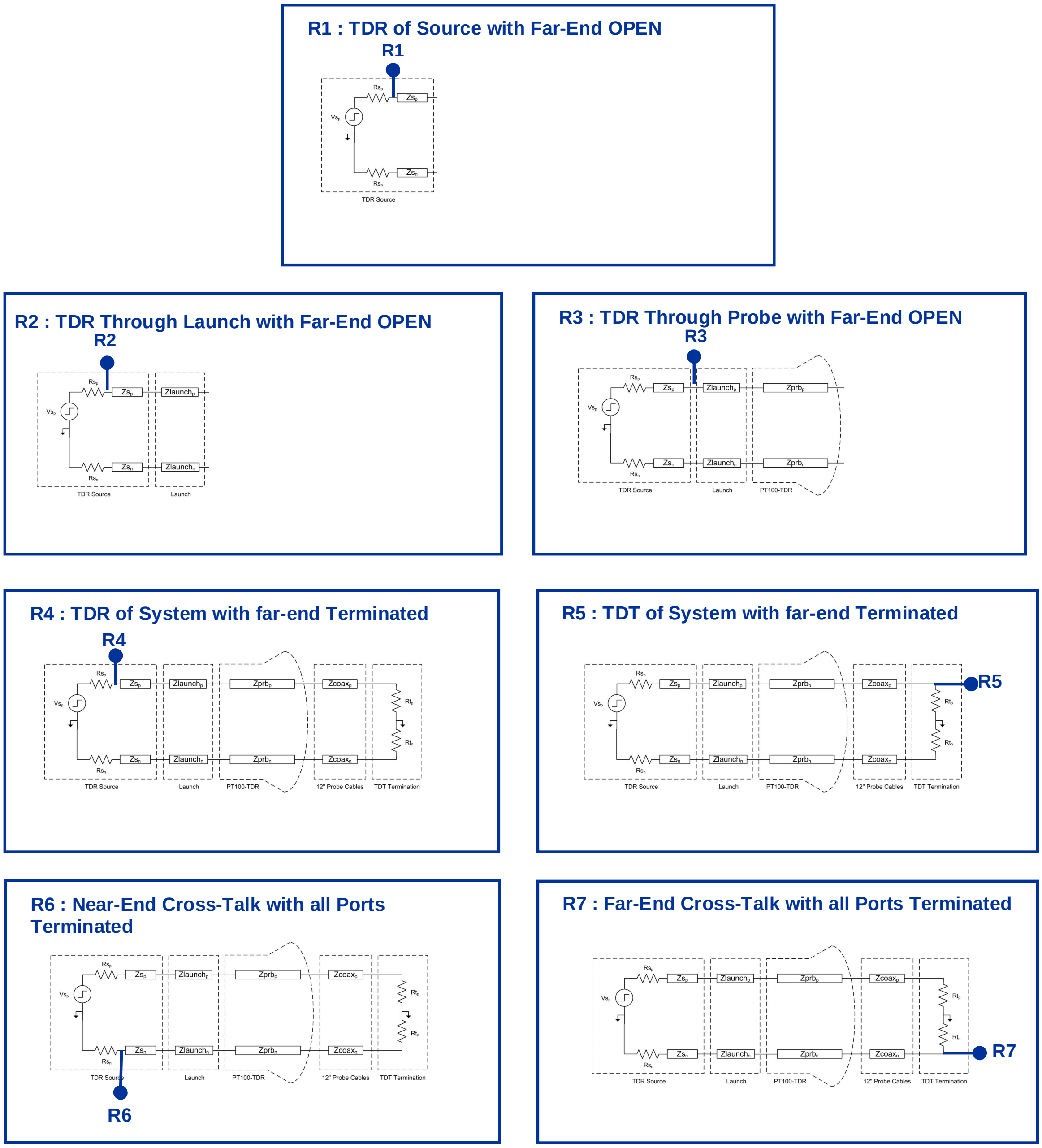


Figure 5. In-Line PT100-TDR Characterization Setup

We define the following test configurations and observation nodes in order to fully characterize the PT100-TDR system.


R1 : TDR of Source with Far-End OPEN

R2 : TDR Through Launch with Far-End OPEN

R3 : TDR Through Probe with Far-End OPEN

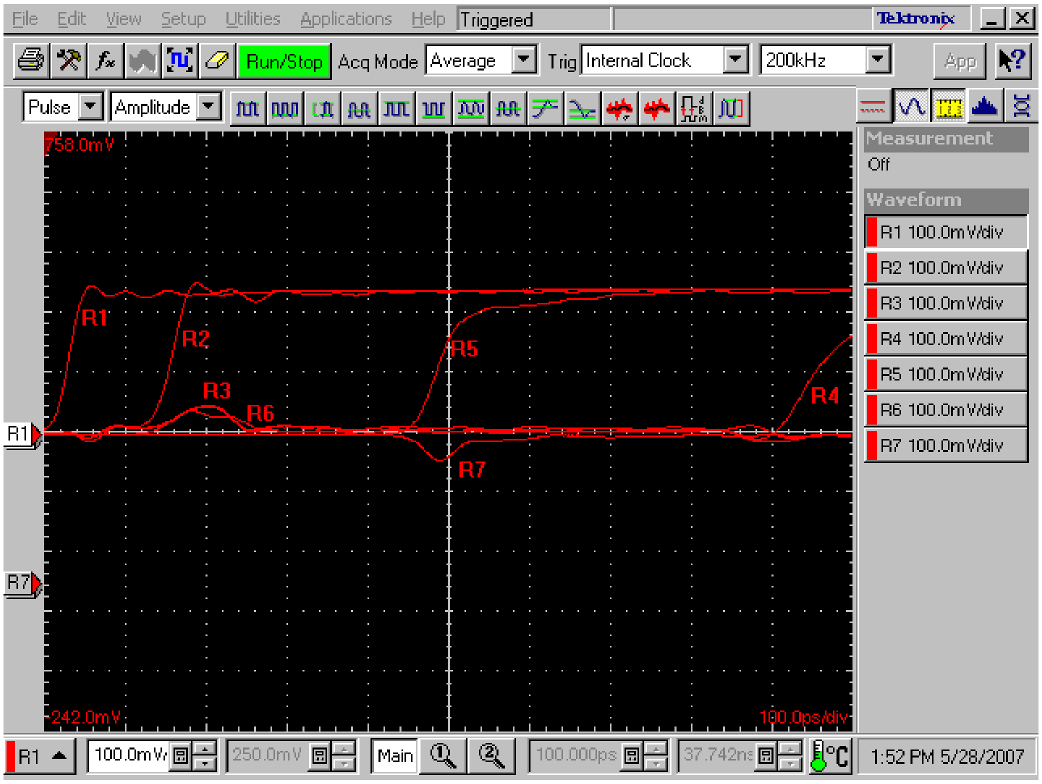
R4 : TDR of System with far-end Terminated

R5 : TDT of System with far-end Terminated

R6 : Near-End Cross-Talk with all Ports Terminated

R7 : Far-End Cross-Talk with all Ports Terminated

Figure 6. In-Line PT100-TDR Node Definition



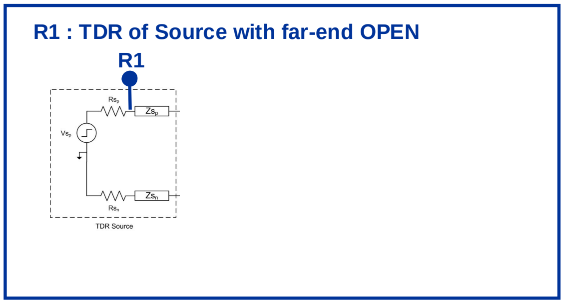
Acq Mode Average
Trig Internal Clock
200kHz

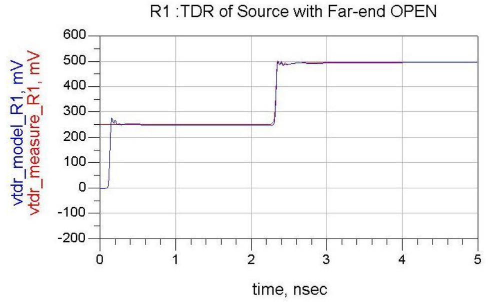
R1 100.0mV/div
R2 100.0mV/div
R3 100.0mV/div
R4 100.0mV/div
R5 100.0mV/div
R6 100.0mV/div
R7 100.0mV/div

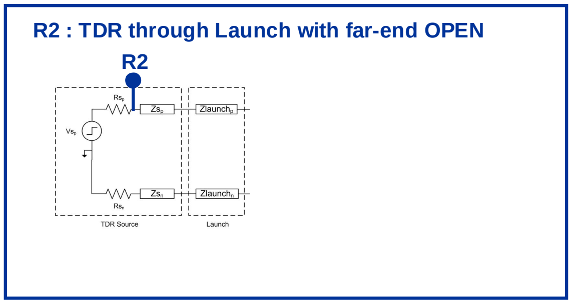
R1 100.0mV 250.0mV 100.000ps 37.742ns

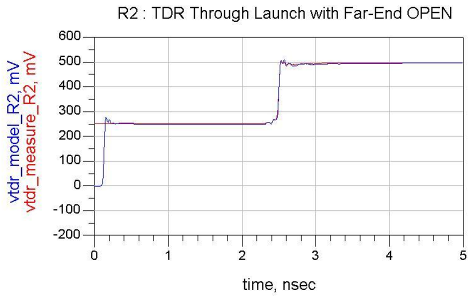
Figure 7. In-Line PT100-TDR Measurement Results

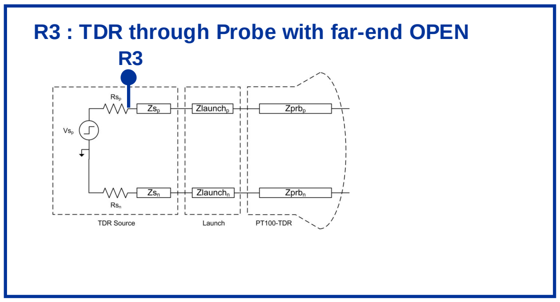
The results from the oscilloscope are then brought into the *ADS* simulation environment and an equivalent SPICE model was constructed of each component.

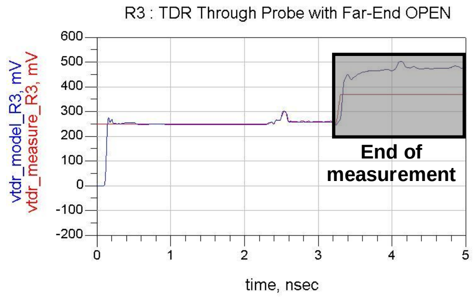


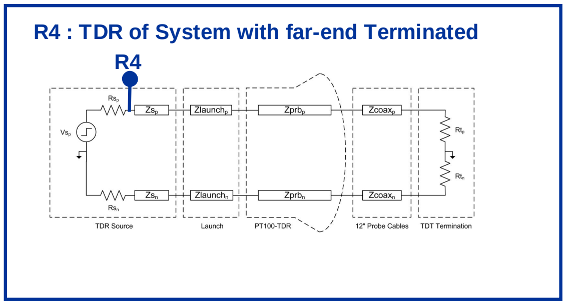


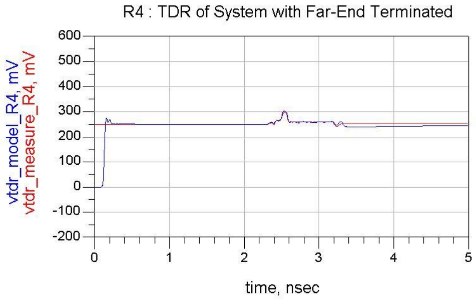


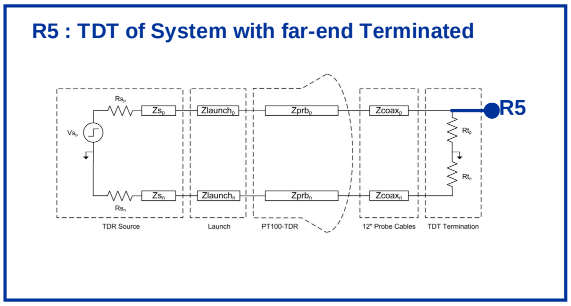


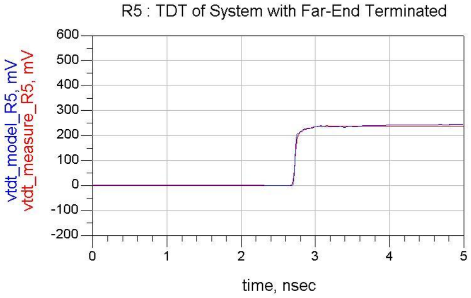


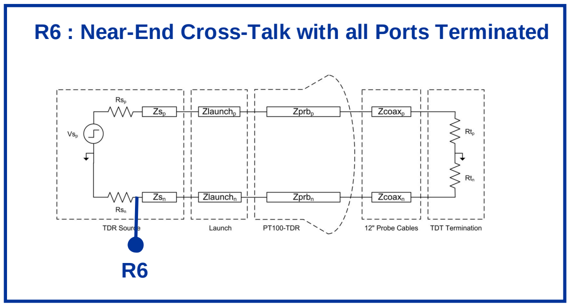


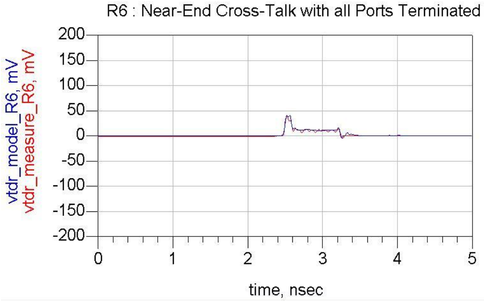


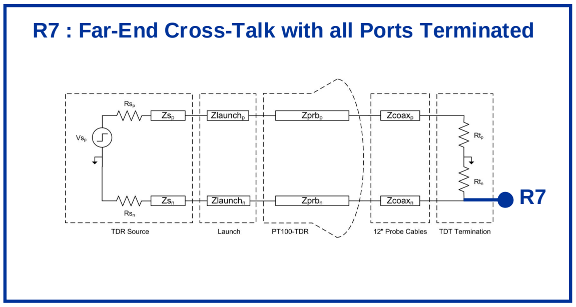












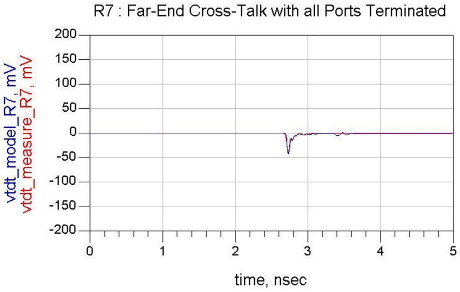


Figure 8. In-Line PT100-TDR Measured vs. Modeled Results

The equivalent models that were constructed mainly consisted of RLC components. The amount of transmission line components was minimized to improve simulation run time.

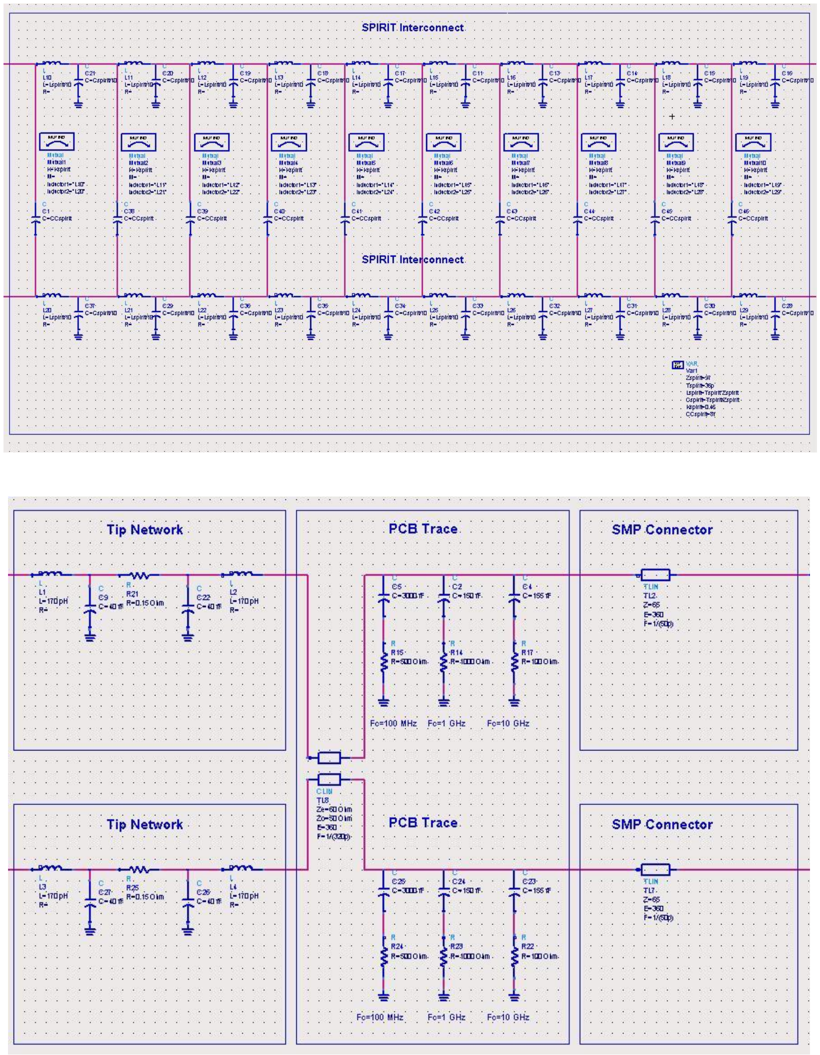


Figure 9. Equivalent SPICE Circuits for In-Line PT100-TDR Configuration

From these equivalent models, the test system can be removed and ideal sources can be used in SPICE to determine the true performance of *only* the probe fixture. This model is accurate in both the time and frequency domain so the Step Response and S-Parameters can be obtained. The frequency that the model is accurate to depends on the frequency that the measurements were taken at. For this project, the TDR oscilloscope was able to stimulate and acquire information at 18GHz. However, the model complexity can be scaled down to a lower frequency by using fewer components. For this project, the model was constructed with enough segments for accuracy up to 5GHz.

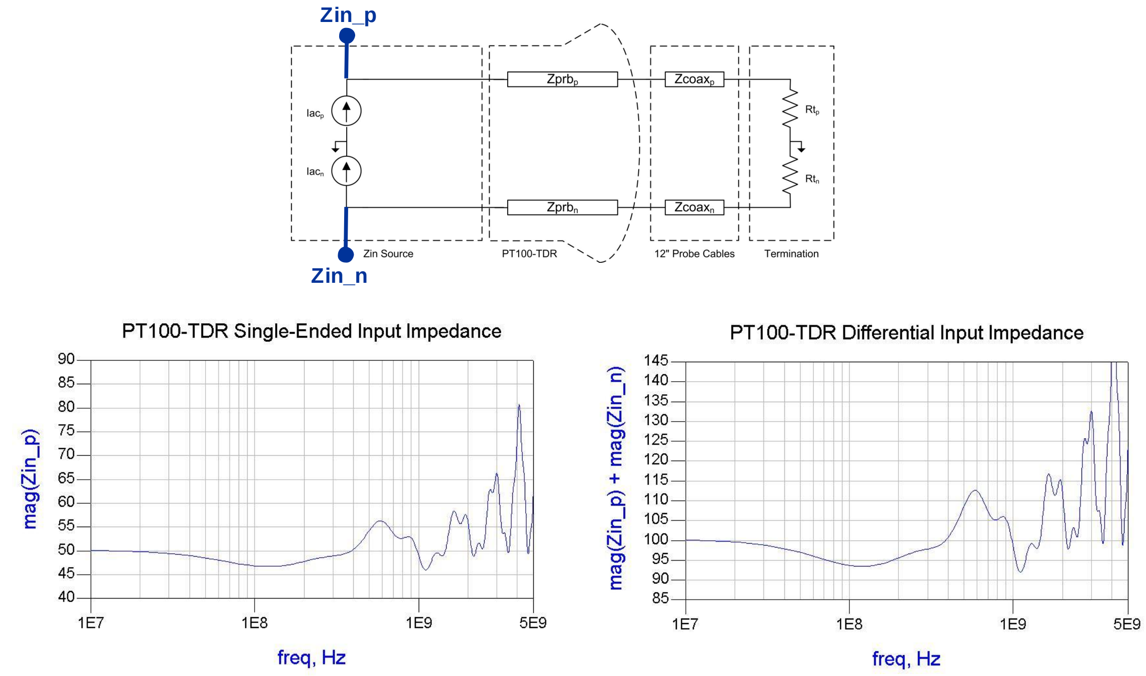


Figure 10. Input Impedance for the In-Line PT100-TDR Configuration

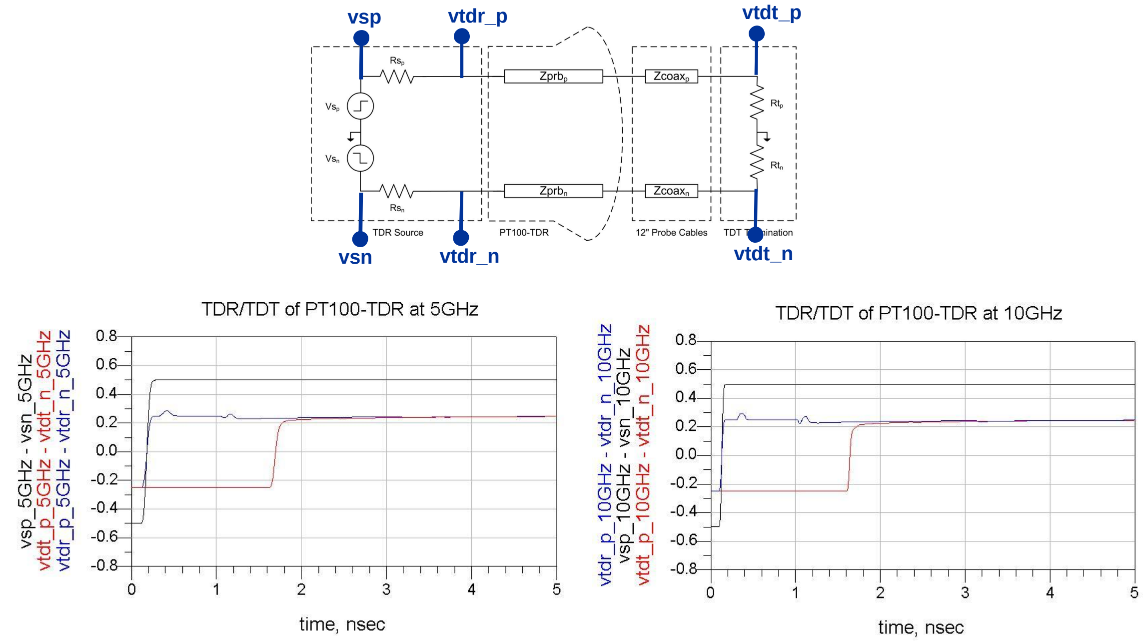


Figure 11. TDR/TDT Impedance for the In-Line PT100-TDR Configuration (70ps Ideal Input Step)

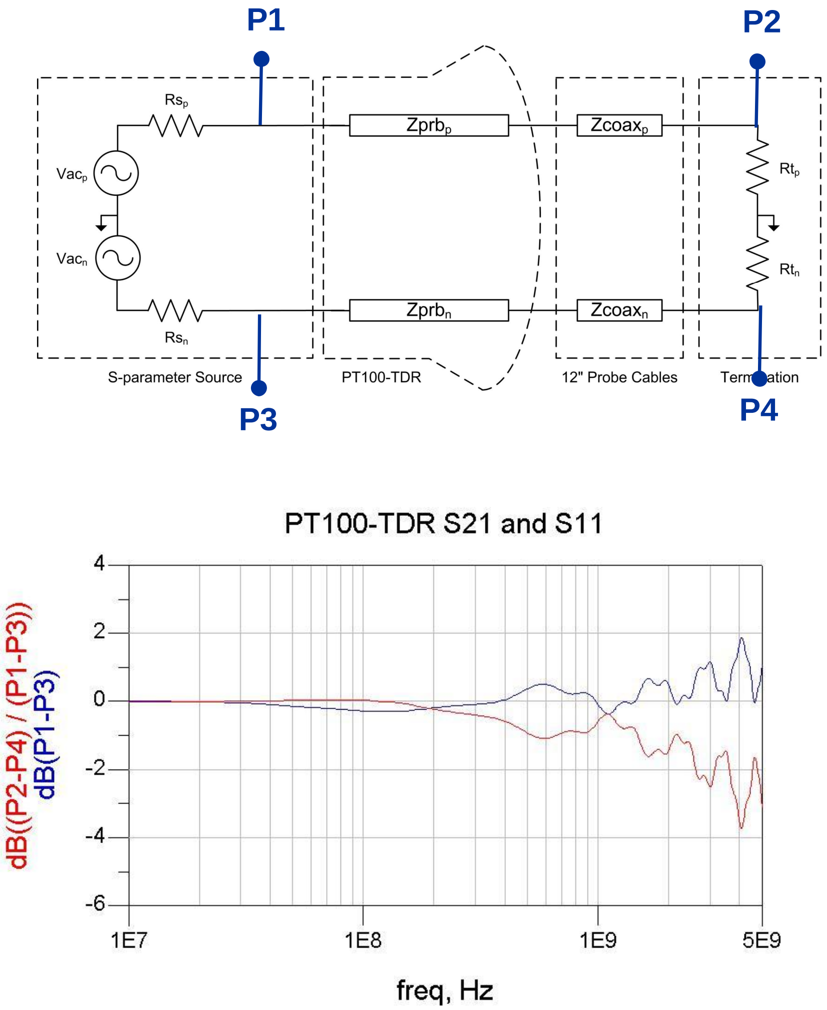


Figure 12. S-Parameters for In-Line PT100-TDR Configuration

4.7 PT100-DC In-Line Probe Fixture Model

The same process is used to construct an equivalent model for the probe fixture when it is configured as a 7:1 resistive divider. Much of the model has been constructed from the PT100-TDR configuration. However, the insertion of a 300 ohm resistor in the tip of the probe fixture changes the responses of some of the inductance and capacitance in the interconnect. This creates a slightly different model of the interconnect model.

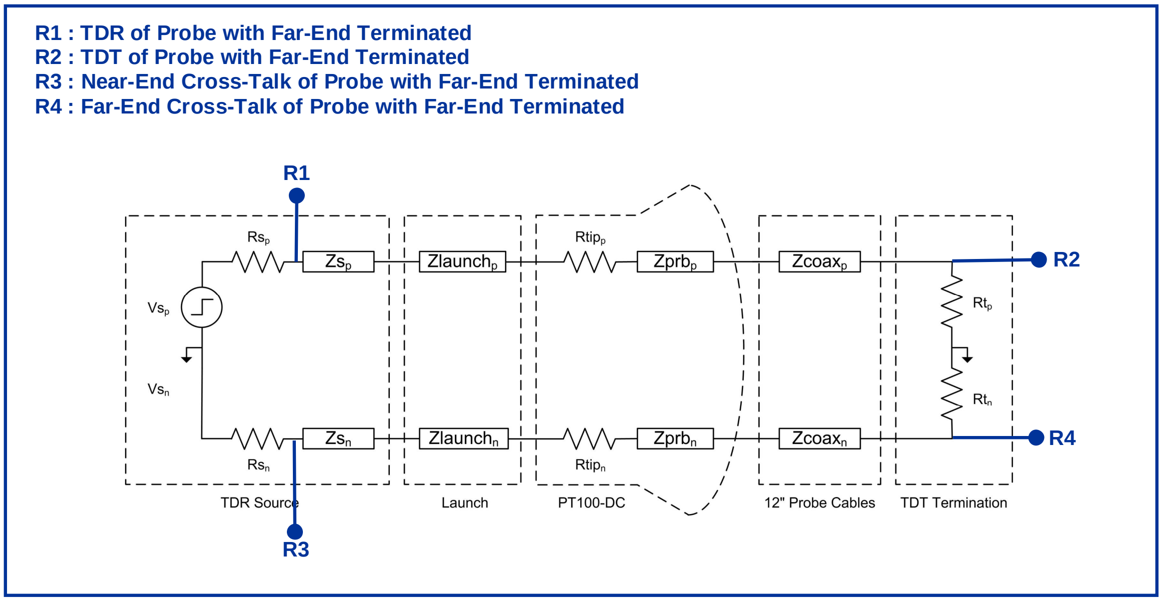


Figure 13. In-Line PT100-DC Characterization Setup

Triggered

Acq Mode Average

Trig Internal Clock

200kHz

Measurement

Off

Waveform

R1 100.0mV/div

R2 100.0mV/div

R3 100.0mV/div

R4 100.0mV/div

R4 100.0mV/

-250.0mV

100.000ps

37.742ns

3:24 PM 5/28/2007

Figure 14. In-Line PT100-DC Measurement Results

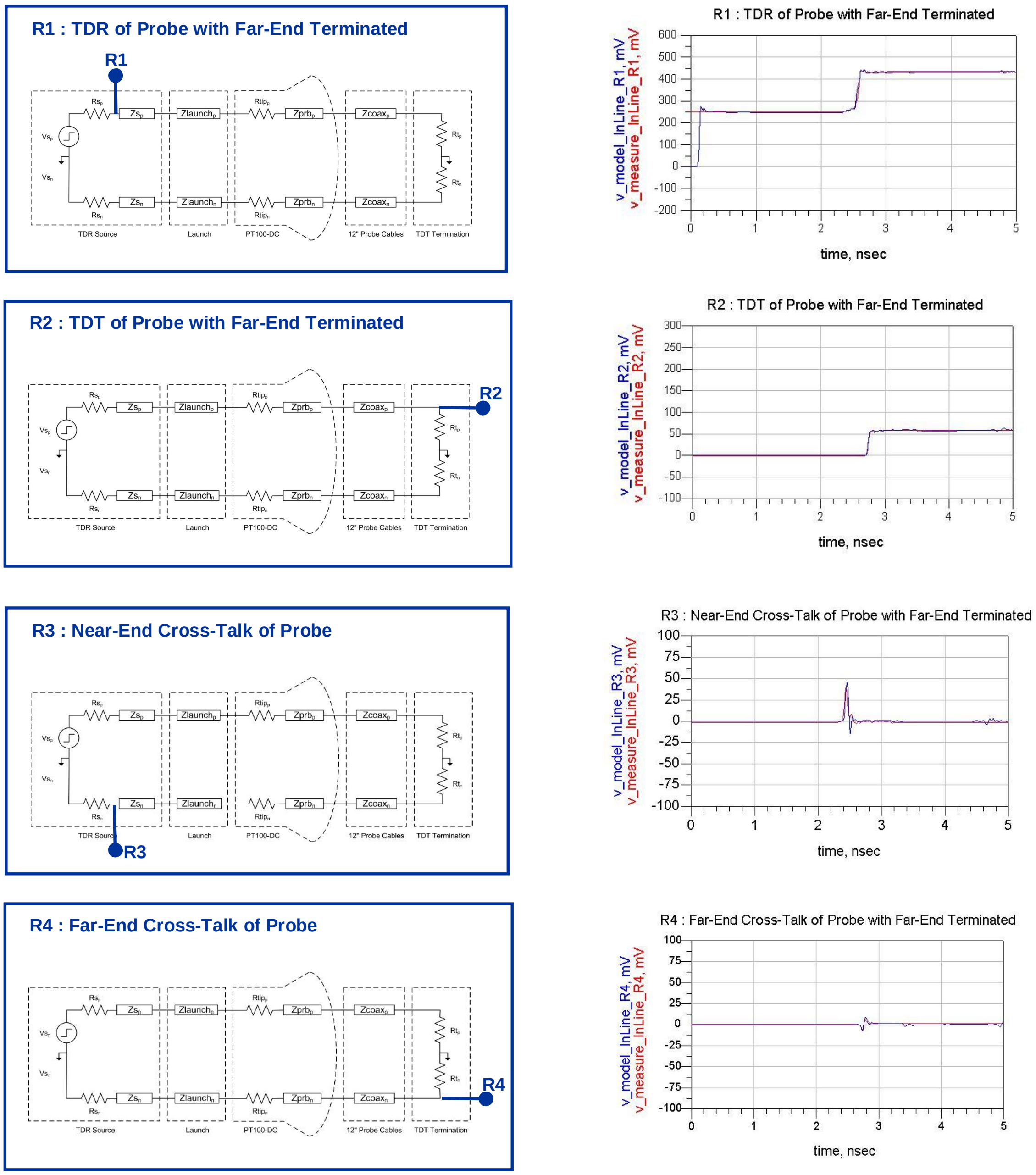


Figure 15. In-Line PT100-TDR Measured vs. Modeled Results

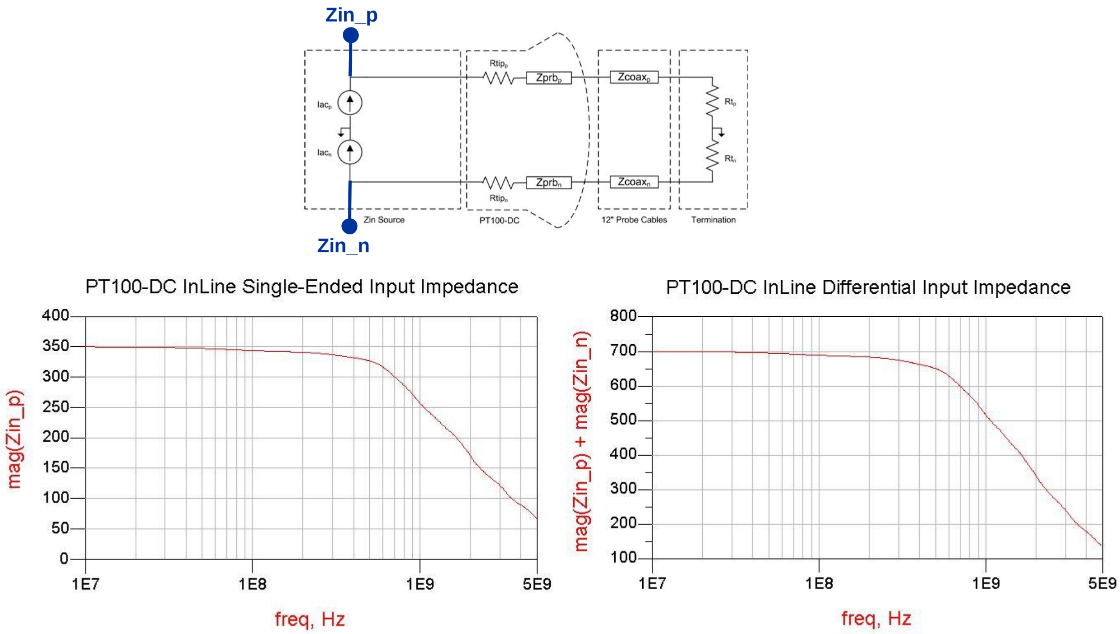


Figure 16. Input Impedance for the In-Line PT100-DC Configuration

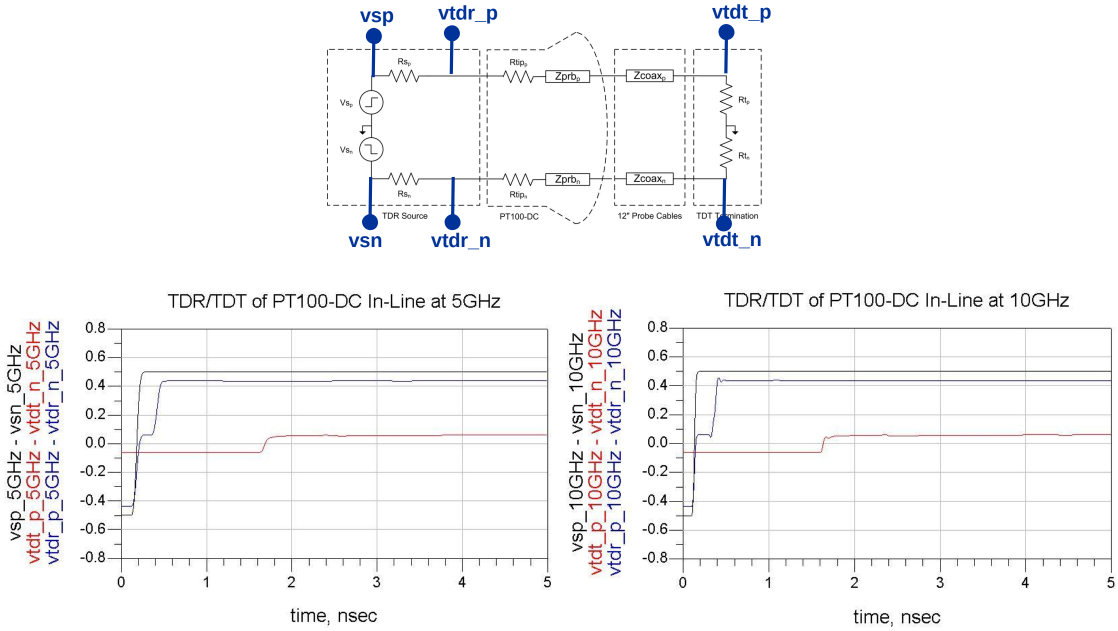


Figure 17. TDR/TDT Impedance for the In-Line PT100-DC Configuration
(70ps Ideal Input Step)

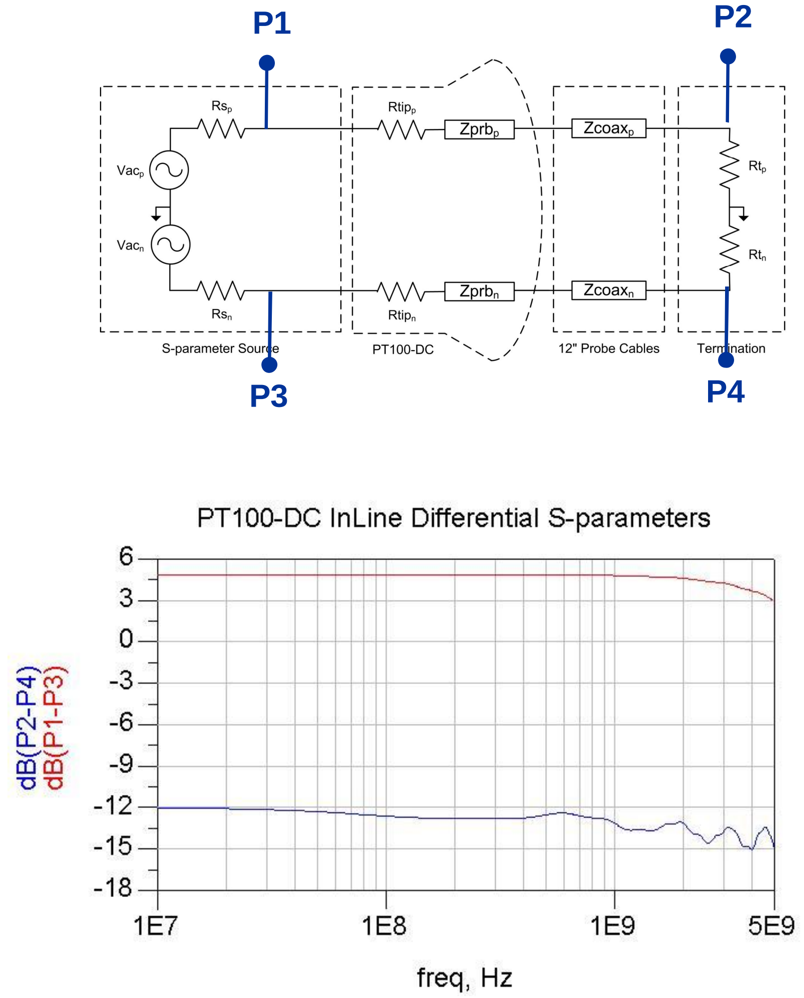


Figure 18. S-Parameters for In-Line PT100-DC Configuration

4.8 PT100-DC Shunt Probe Fixture Model

The same process is used to construct an equivalent model for the probe fixture when it is configured as a 7:1 resistive divider in a *Shunt* configuration. The shunt configuration is typical of how an engineer would use this fixture to passively observe signals on a PCI-express link using an oscilloscope.

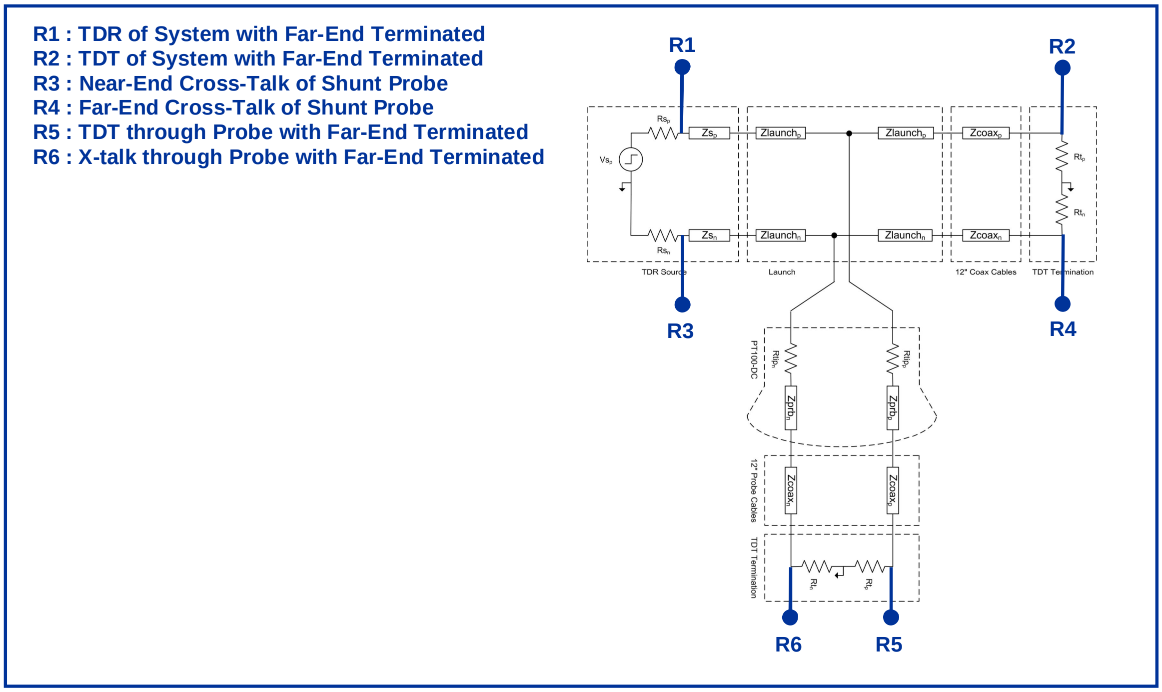
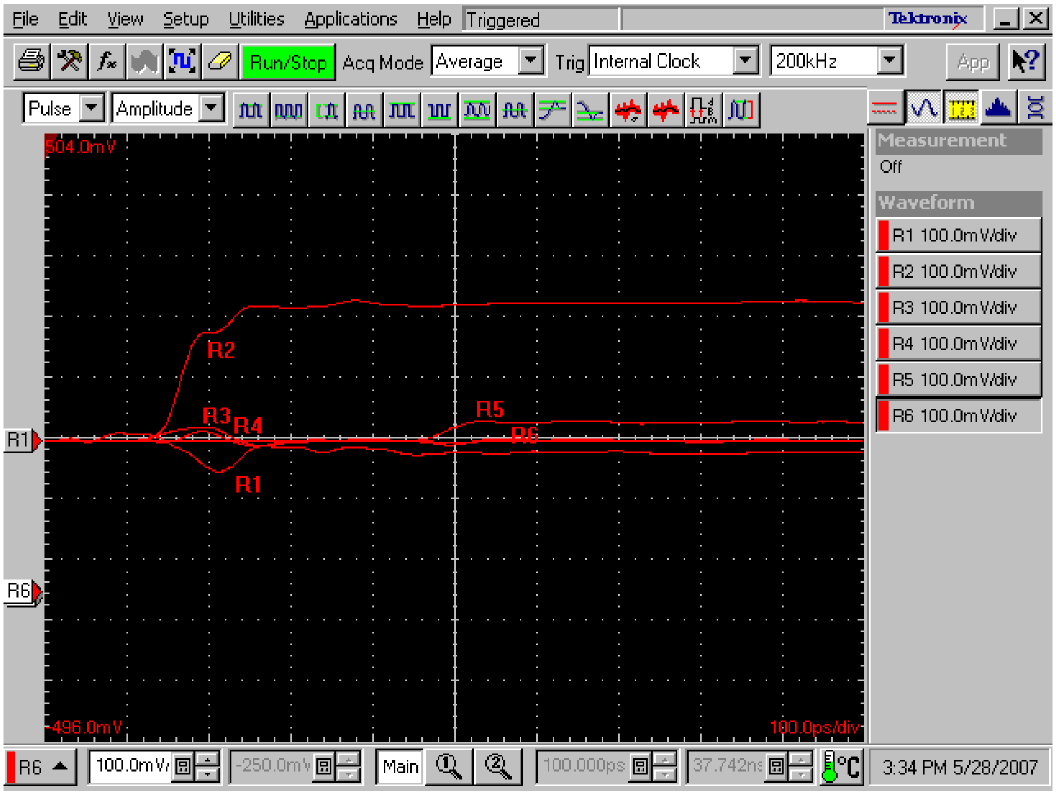


Figure 19. Shunt PT100-DC Characterization Setup



Triggered

Acq Mode Average

Trig Internal Clock

200kHz

Pulse

Amplitude

Measurement

Off

Waveform

R1 100.0mV/div

R2 100.0mV/div

R3 100.0mV/div

R4 100.0mV/div

R5 100.0mV/div

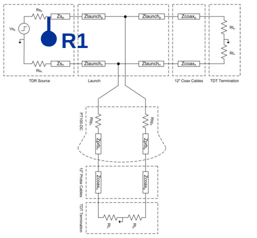
R6 100.0mV/div

R6 100.0mV/ -250.0mV 100.000ps 37.742ns

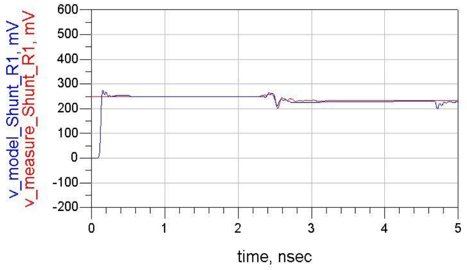
3:34 PM 5/28/2007

Figure 20. Shunt PT100-DC Measurement Results

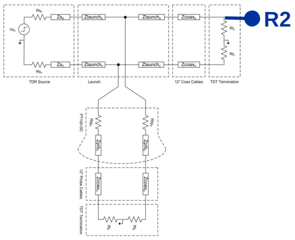
R1 : TDR of System with Far-End Terminated



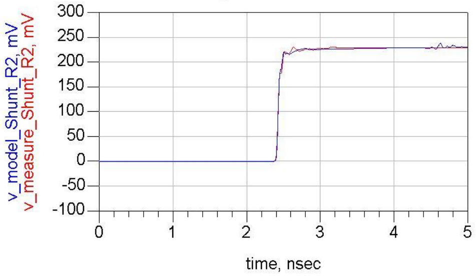
R1 : TDR of System with Far-End Terminated



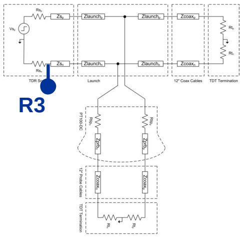
R2 : TDT of System with Far-End Terminated



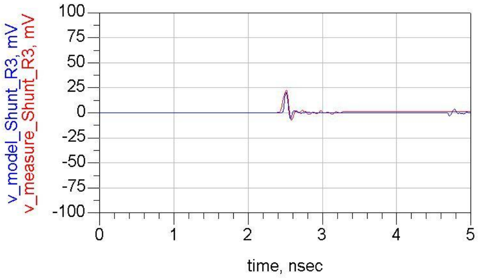
R2 : TDT of System with Far-End Terminated



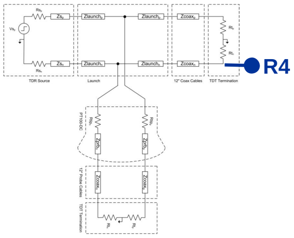
R3 : Near-End Cross-Talk of Shunt Probe



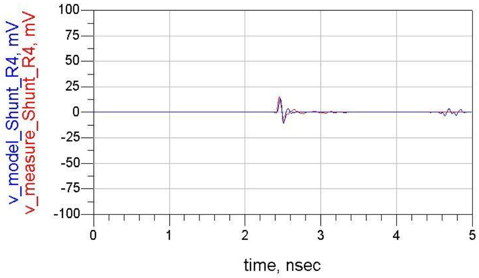
R3 : Near-End Cross-Talk of Shunt Probe



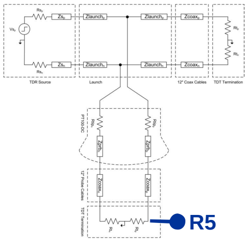
R4 : Far-End Cross-Talk of Shunt Probe



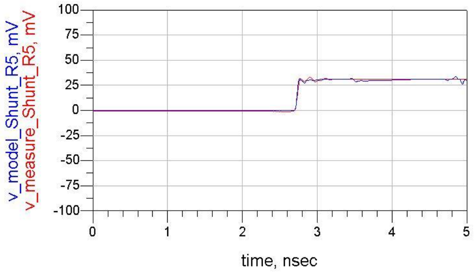
R4 : Far-End Cross-Talk of Shunt Probe



R5 : TDT through Probe with Far-End Terminated



R5 : TDT through Probe with Far-End Terminated



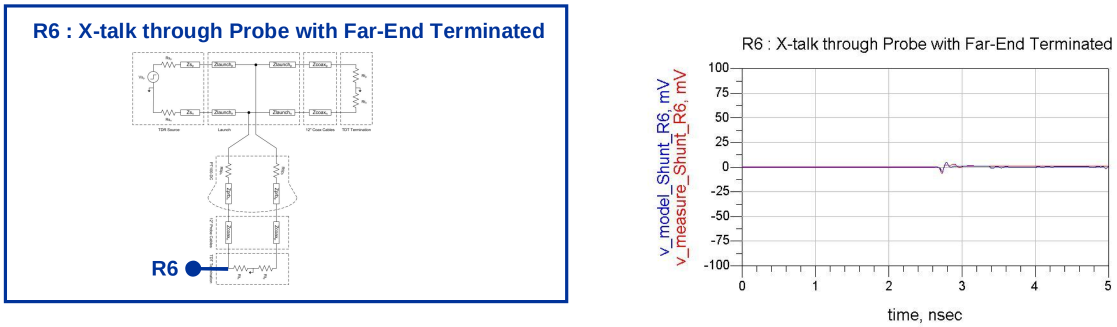


Figure 21. Shunt PT100-DC Measured vs. Modeled Results

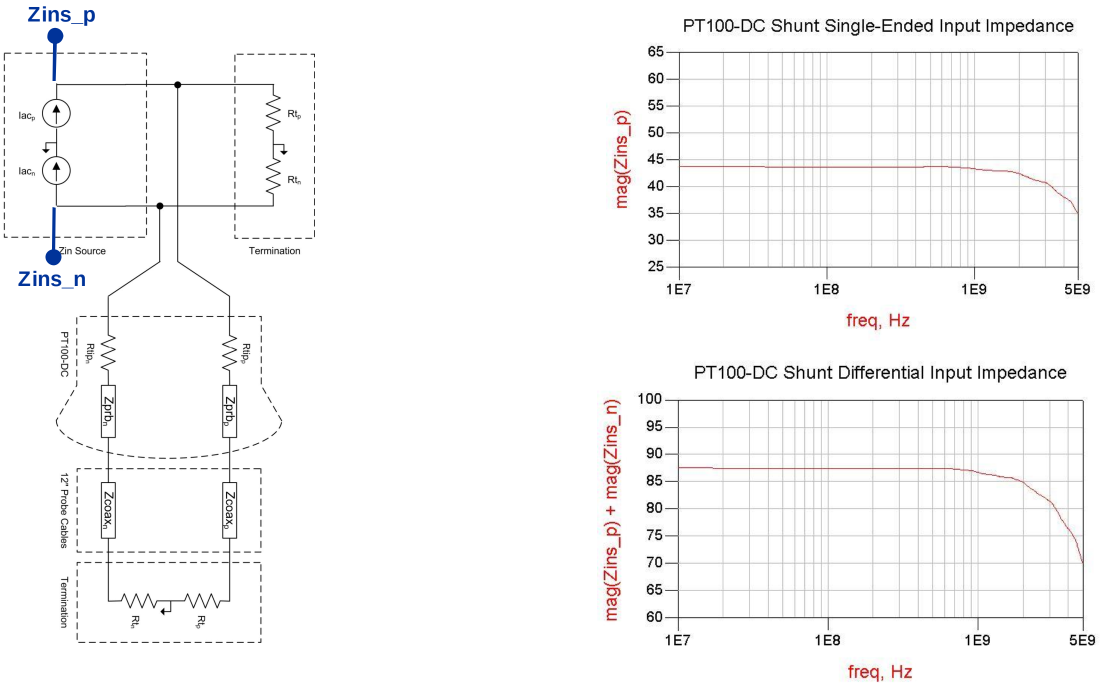


Figure 22. Input Impedance for the Shunt PT100-DC Configuration

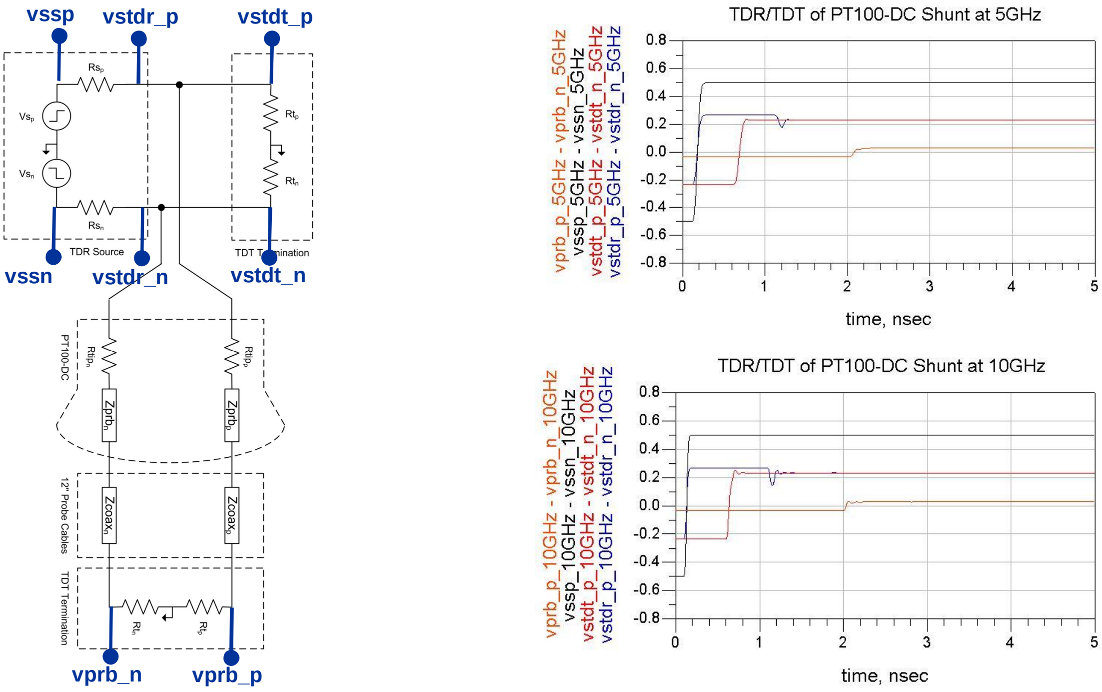


Figure 23. TDR/TDT Impedance for the Shunt PT100-DC Configuration (70ps Ideal Input Step)

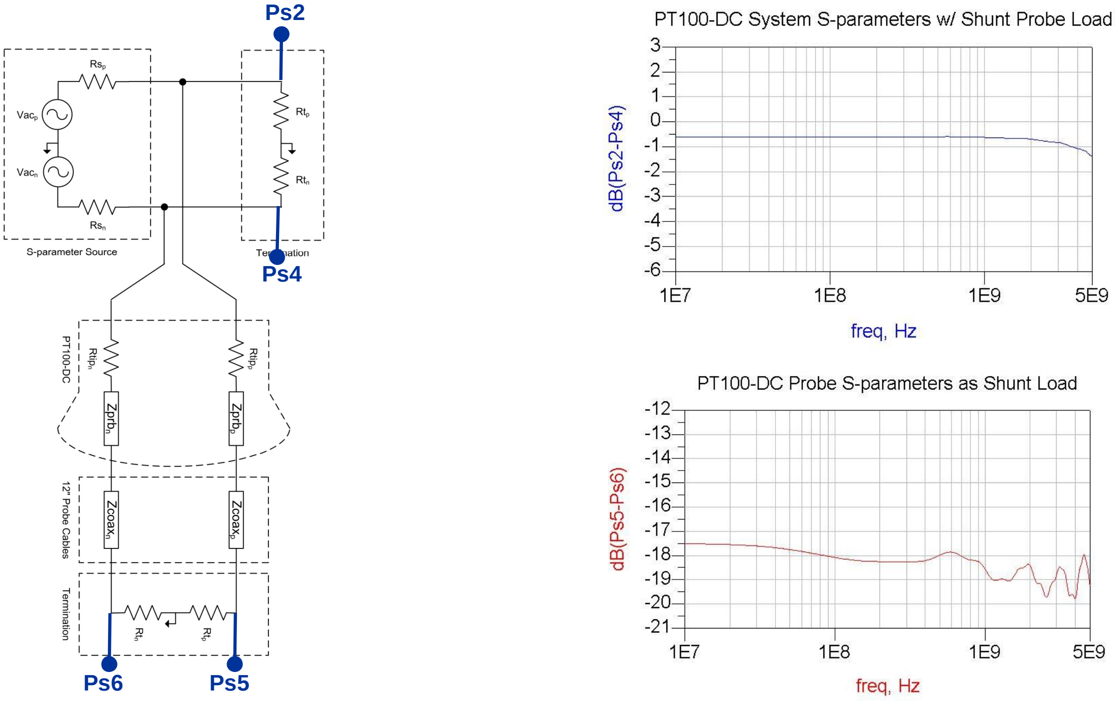


Figure 24. S-Parameters for Shunt PT100-DC Configuration

5. Conclusion

This paper presented a characterization methodology to create an equivalent SPICE model of a microwave fixture. The methodology used an incremental approach that allowed each section of the fixture to be characterized individually and then to be included into a larger system model. The end result was an equivalent model of the entire test setup including stimulus waveform, fixture DUT, and the DUT itself. Once the model was created, the model of the test setup was removed yielding only the equivalent model for the DUT. The model of the DUT was then stimulated using ideal sources (AC current, AC voltage and a step voltage) in order to determine its input impedance, S-parameters, and step response. The frequency of the ideal stimulus was reduced to give information only in the frequency spectrum of interest (DC to 5GHz). This technique is ideal for engineers doing characterization of microwave fixtures that need to gain an intuitive feel for which components are contributing to the loss in the system. The resultant SPICE model for the probe fixture is ideal for transient simulations due to its construction with RLC elements. This reduces simulation run time in time-domain analysis. The model created is applicable for both time and frequency domain simulations. System level engineers using this probe fixture to make measurements can use the model to predict its effect on their target signals in addition to de-embedding the fixture's effect from their own measurements.