

Designing transitions using Time Domain Reflectometry

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Abstract:

TDR analysis is a very useful tool when designing transitions as it can show impedance over distance so discontinuities are observed. This paper will describe the TDR function in vector network analyzers, show how to set up the measurement and how to interpret the results. The example of a board launch will be used to show the process of optimizing a launch using TDR.

Introduction

Time Domain Reflectometry (TDR) is a very useful tool for designing transitions such as the transition between coaxial connectors and PC boards. The TDR function will display the impedance over time showing the place and nature of discontinuities that are due to impedance changes.

This paper will discuss the aspects of TDR measurements that are relevant to the analysis of a transition. The complete range of TDR measurements and applications will not be explored.

How Does TDR Work?

A true TDR tester injects a pulse into a transmission line and the reflections are shown on an oscilloscope. The rise time of the pulse determines the bandwidth.

How Does the Reflection Differ with Impedance?

Reflections displayed represent discontinuities due to a change in the impedance along a transmission line. The magnitude of the discontinuity determines the magnitude of the reflection. Zero units represents the characteristic impedance of the line, typically 50 ohms.

The direction of the reflection on the display, either positive or negative, is determined by whether the impedance that caused the reflection is inductive or capacitive. The impedance formula for a transmission line is:

$$Z = \sqrt{\frac{L}{C}}$$

The reflections are shown on an oscilloscope. Based on the transmission line formula reflections that show greater than the characteristic impedance are inductive and reflections that show smaller than the characteristic impedance are capacitive.

An example transmission line and the corresponding ideal TDR response is shown in Figure 1. It starts with a 50 ohm characteristic impedance then jumps to 55 ohms (more inductive) then dips to 45 ohms (more capacitive) then returns to the 50 ohm characteristic impedance.

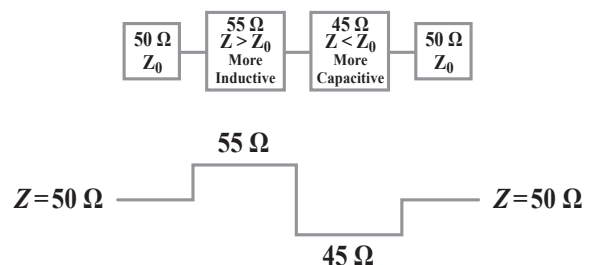


Figure 1: Example transmission line and TDR response

Relationship Between Time Domain and Frequency Domain

Review of Fourier Analysis

Fourier's theory is that any repetitive signal can be expressed as a summation of single frequency signals. Take a square wave for example; (Figure 2)

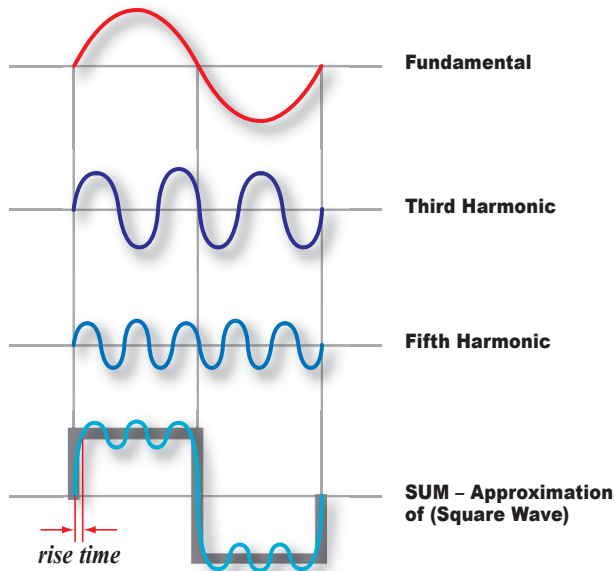


Figure 2: Fundamental frequency and harmonics create an approximation of a square wave.

it is the infinite summation of harmonics of a sine wave with the same frequency as the square wave.

$$y = \frac{4 \sum_{n=1}^{\infty} \frac{\sin(2\pi f (2n-1) t)}{2n-1}}{\pi}$$

There are no true square waves in electronics so the rise time of a square wave determines the bandwidth or the highest frequency harmonic in a Fourier series describing the square wave.

Plotting the single frequency summation on a frequency plot gives the frequency domain representation of a repetitive signal. Translating a time domain signal to frequency domain is done through a Fourier transform and from frequency domain to time domain is done through an inverse Fourier transform (Figure 3).

How Does the TDR Function on a VNA Work?

A VNA is a frequency domain device. An inverse-Fourier transform can be used to convert frequency domain to time domain. To do this there has to be a harmonic relation between the frequencies in the frequency domain. A harmonic relationship means that whatever the start frequency is, all of the following frequencies have to be harmonics. This simply means they have to be multiples.

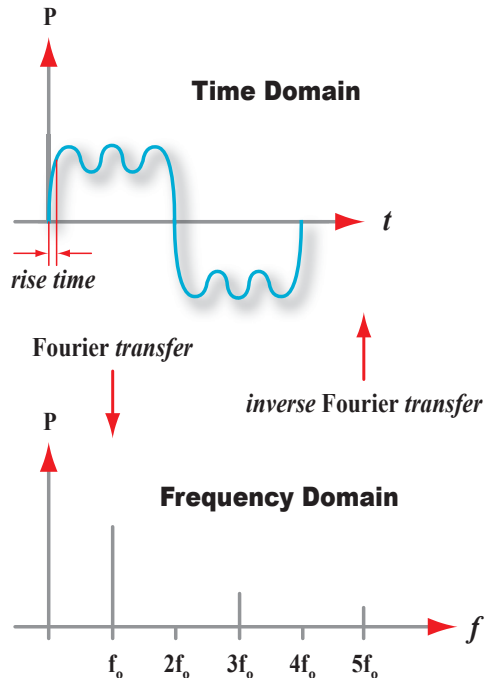


Figure 3: Relationship Between Frequency Domain and Time Domain.

Bandwidth vs. Risetime

The rise time of a signal in time domain determines its bandwidth, in frequency domain the highest frequency of harmonic determines the bandwidth. With modern synthesizers, VNA's can make higher bandwidth TDR measurements than is practical with true TDR measurement systems. For example, a 50 GHz bandwidth measurement corresponds to a 7 psec risetime pulse. It is very difficult to create real pulses with this small a risetime.

Bandwidth vs. Risetime

$$BW = \frac{.35}{t_r} \quad RT = 7 \text{ psec} \quad BW = \frac{.35}{7 \text{ psec}} = 50 \text{ GHz}$$

How to Analyze a Transition Using TDR

VNA Calibration

To make a TDR measurement the calibration of the VNA has to be done with a harmonic sweep. Any calibration method can be used and for TDR it can be single port. There is a minimum number of points that are required and this will be explained in later sections.

TDR Set-up

The measurement channel should be S11. The TDR setting to get impedance over distance/time are: low pass step, real units at 10 milli-units per division, and minimum window. The resolution can be adjusted for larger discontinuities.

Example

To demonstrate the usefulness of a TDR in board transition designs the following example will step through the analysis of an actual design. This example is a 1 inch test board for 2.4 mm end launch connectors fabricated out of 30 mil thick Rogers RO4350 material.

The board has a grounded coplanar structure and this is tested through 50 GHz (Figure 4). South-west Microwave Standard Format of S-Parameter Data is S11 on the bottom of the graph in VSWR with scale of 0.2 per division, and S21 on the top of the graph in Log Mag with a scale of 1 dB per division.

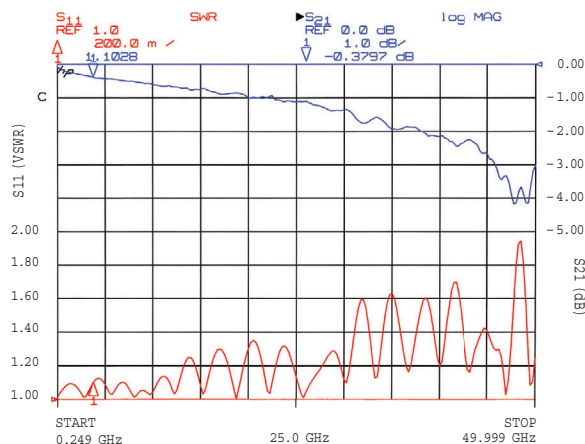


Figure 4: Test Data 30 mil Coplanar Test Board

A TDR plot is generated (Figure 5). To interpret the TDR plot the electrical lengths of each section needs to be calculated. The length of the connector is .308" and it has an air dielectric. This calculates to an electrical length of 26 picosecond (psec). The launch pin through the transition block is .167" long and the dielectric is Teflon® (PTFE).

This calculates to an electrical length of 20 psec. This adds up to a total of 46 psec which on an Agilent VNA is displayed as 92 psec as Agilent includes the return time on their TDR display.

Using the calculated electrical lengths the actual TDR plot can be interpreted. The TDR display starts with 0 units for the nominal impedance which is 50 ohms. The change in impedance can be estimated using the conversion of 10 milli-units per ohm. In this example the circled point is about -40 milli-units which converts to 46 ohms. Looking at the physical structure this discontinuity can be explained by the pin sitting on the trace so it is assumed to be real. It is also assumed that the 10 milli-units discontinuity just before is not real. A useful tool to help analyze these structures are 3-D electromagnetic simulators.

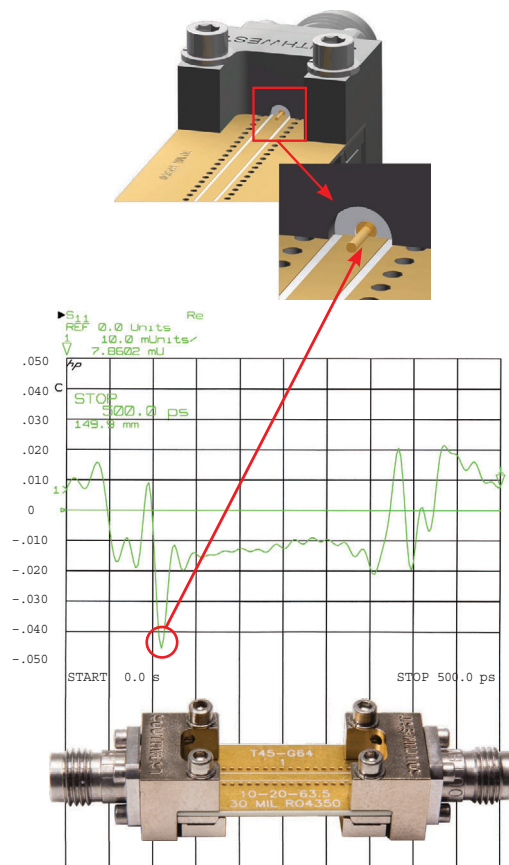


Figure 5: TDR of Coplanar Test Board

How to Optimize a Transition Using TDR

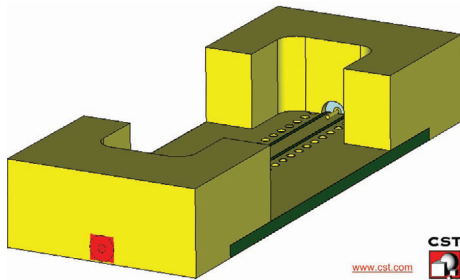
3-D Simulation

Simulation can be used to predict the results of these types of structures then changes can be made and the results of that change can be viewed without having to fabricate and test actual hardware. Decent correlation of the known performance of this test board was achieved with CST Microwave Studio® (CST MWS) Simulation. CST provided the simulations.

CST MWS Model

The 3-D simulation model is created by only looking at the transition blocks and the test board (Figure 6).

Figure 6: CST MWS Model Without Connectors



Simulation results verify that the biggest discontinuity in the transmission line is the transition from coax to PCB (Figure 7).

TDR

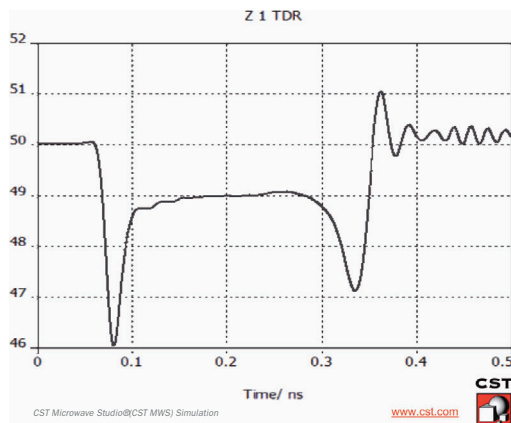


Figure 7: The TDR shows the board impedance below 50 ohms and a capacitive dip on either end where the launch pin sits on the board. This also corresponds to measured data.

The worst transmission line is the PCB. The two coaxial connectors are well matched and have very low loss, so even without them in the simulation, a very good correlation to the actual performance can be achieved.

Simulation Results

The insertion loss has a dip at 45 GHz and the VSWR slowly rises over frequency from below 1.2:1 to 1.6:1 through 45 GHz. Both of these are characteristic of the test board and show good correlation of simulated to measured.

Simulated S-Parameter data matches very well with measured data (Figure 8).

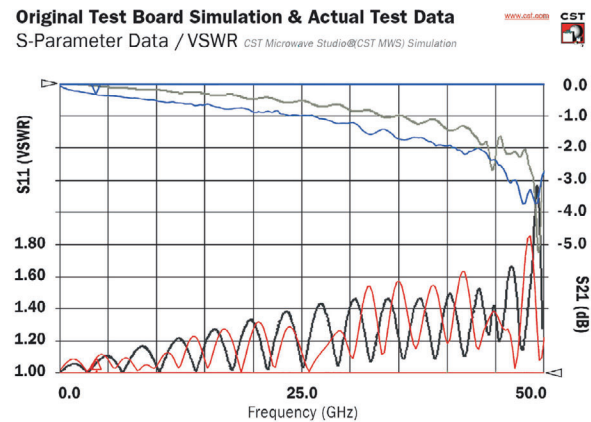
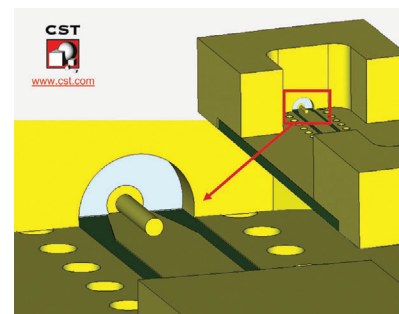


Figure 8: Simulation of original test board compared to actual measured data

Maximizing the Test Board Performance

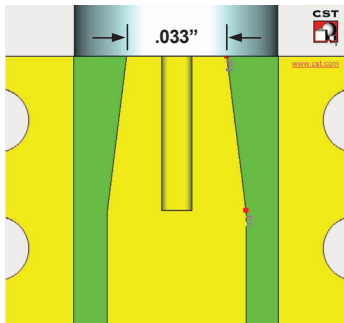
Inductance needs to be added to the board layout to offset the added capacitance of the launch pin. This is done with a taper (Figure 9) and the taper is designed in such a way as boards can be modified with an X-Acto knife for those that do not have a simulation tool.

Figure 9: Taper



The optimized taper design (Figure 10) was developed using CST Microwave Studio's optimization routine.

Figure 10: Optimized Taper



The simulation results show the capacitive dip is reduced (Figure 11) producing excellent results for S11 (Figure 12), much better than could be realized in practice and the insertion loss is very smooth up to the normal 45 GHz glitch always seen.

Figure 11: Simulated TDR Comparison: Optimized Taper No Taper

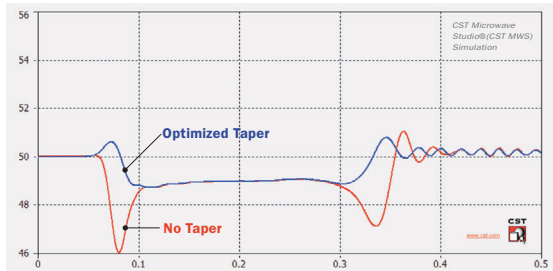


Figure 12: Optimized Taper S-Parameter Simulated Data

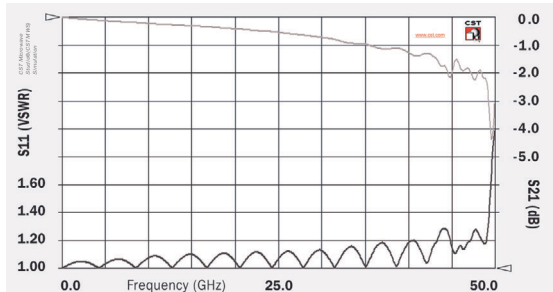
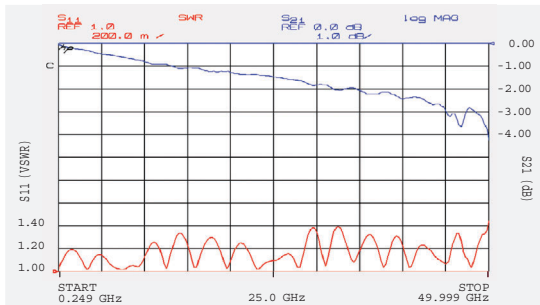


Figure 13: Actual Test Data for 30 mil Coplanar Board



The actual board is shown in (Figure 14) and the measured data in (Figure 13).

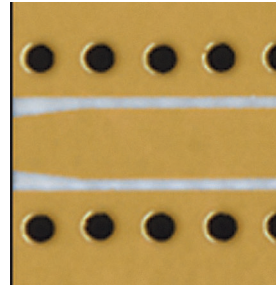


Figure 14: Enlarged View of Coplanar Test Board Showing Optimized Taper

Test Set-up Critical for Useful TDR Results

The measurements in this paper were made on an Agilent 8510C setup as shown (Figure 15).



Figure 15: Overview of Agilent 8510C Workstation

To make accurate TDR measurements the loss has to be minimized. To ensure this, it is recommended that only one cable (Figure 16) is used in the test setup and the port without the cable is used for all of the TDR measurements (Figure 17).



Figure 16: Port Configuration of Agilent 8510C Workstation with a Single Cable

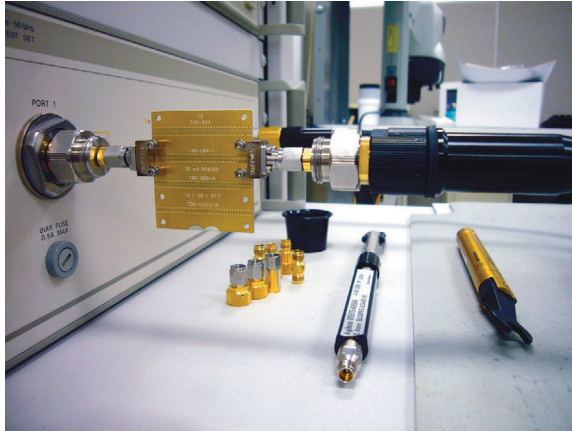


Figure 17: Agilent 8510C Workstation with Device Under Test Connected to Port 1

The higher the frequency range the better the resolution and there is a minimum number of points needed depending on the electrical length of the device under test. TDR measurements are set up as low pass step in real units with a minimum window.

Agilent 8510C Analyzer Workstation

- ▶ 12-term SOLT calibration.
- ▶ Sliding loads were used.
- ▶ Single cable – DUT connected directly to port 1.
- ▶ Non-insertable handled by swapping phase matched adapters.
- ▶ 201 points.
- ▶ Harmonic sweep for time domain.

Differences on Anritsu Equipment

Anritsu VNA's (Figure 18, 19) also have a TDR function which are the same in principal as Agilent's but some terminology and details are different. The first major difference is that Anritsu's time scale shows the one way distance to the discontinuity, not the return trip distance as Agilent's shows. For example, the test board used in this paper is 500 psec long on an Agilent VNA but it is only 250 psec long on an Anritsu. The setup for measurement is still lowpass step, real units, 10 milli-units per division but the windowing is called rectangular instead of minimum.

Anritsu 37297D (Differences from Agilent)

- ▶ One way distance is displayed instead of return trip. For example 500 psec on Agilent will be 250 psec on Anritsu.
- ▶ Same basic setup: lowpass step, real units, 10 milli-units per division
- ▶ Windowing is "rectangular" instead of "minimum".

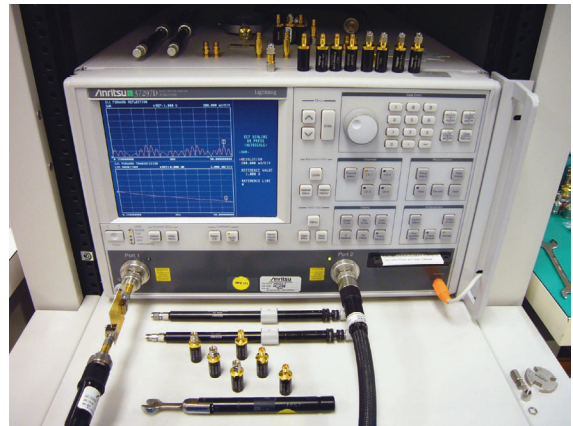


Figure 18: Overview of Anritsu 37297D Workstation

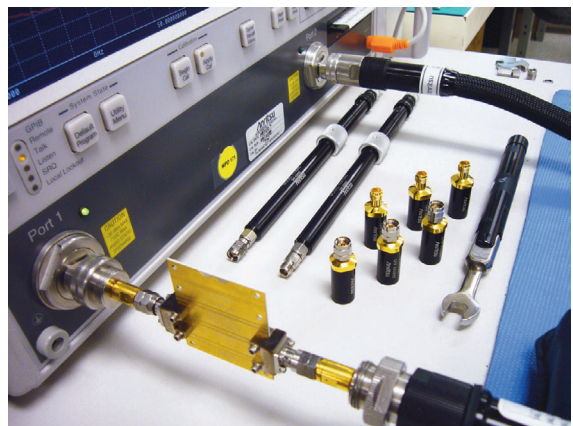


Figure 19: Device Under Test Connected to Port 1

Interpretation of Results: Assumptions / Caveats

The TDR function of a VNA is derived from calculated results which creates its own uncertainties on top of the inherent uncertainties of TDR measurements in general. The biggest point to remember is that after the first discontinuity all other measurements will be skewed to the point where all of the accuracy can be lost. The VNA manufacturers do not specify accuracy for TDR

measurements nor do they typically warn their customers of these issues with the exception of an application note from Agilent, they just state all of the advantages of TDR without addressing any of the accuracy issues.

Scalar Info Only

It is important to remember that the impedance value of a TDR measurement is the real value only and does not include the imaginary. Placing a marker on the TDR display and converting to a Smith chart will also show the value of the real component of the impedance.

Accuracy

There are no stated accuracy specifications for TDR measurements from the manufacturers of which the author is aware. Some experienced users have a good understanding of the accuracy limitations based on previous lessons learned. As a rule of thumb a 10% uncertainty value can be assumed until the first big discontinuity and then do not trust any of the results. This is demonstrated in the masking section.

Measurement Range Limitations (Aliasing)

On a VNA the time domain response is repeated every $1/\Delta f$ seconds. If the length of the device (range) is greater than the repeat time, two or more responses will be seen instead of just one. To increase the range either the number of points can be increased or the frequency range can be increased. Both will have the effect of reducing Δf .

This is mostly a problem in cable testing where cables can be very long. Boards are usually too short to cause this problem.

Resolution

The resolution of a TDR is frequency dependant, the higher the frequency the more resolution. Resolution can also be compromised if there are not enough data points in the sweep. Shown is a 50 GHz sweep with 201 points (Figure 20).

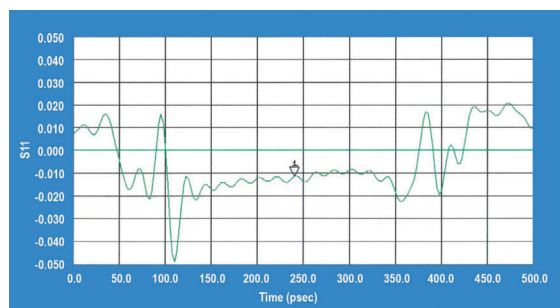


Figure 20: High Resolution (50 GHz, 201 points)

A low frequency graph (Figure 21) shows a TDR on the same board with a 27 GHz, 201 point sweep. The peaks are lost because with a lower frequency there is more distance between the points discerned by the TDR.

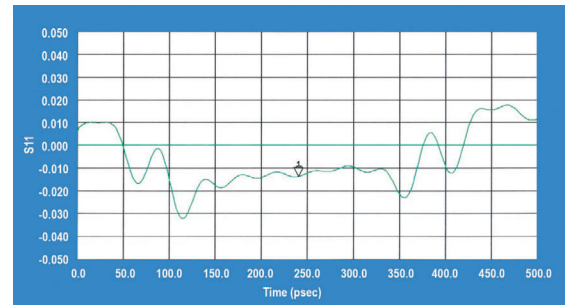


Figure 21: Low Frequency Resolution (27 GHz, 201 points)

A low number of points graph (Figure 22) shows a TDR on the same board with a sweep to 50 GHz with only 51 points. It can be seen that there are not enough points to catch all of the detail available with the 50 GHz bandwidth.

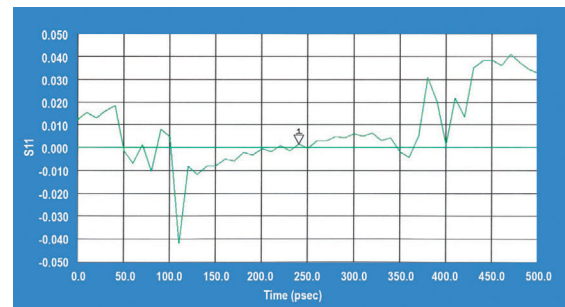


Figure 22: Too Few Data Points Resolution (50 GHz, 51 points)

Masking

A large discontinuity will “mask” the rest of the data. This is because the first discontinuity will affect any energy that gets past it and then affect it again on the return trip.

The first plot is a frequency domain measurement where a bad connector on a test board is creating what is called a “suckout” (Figure 23). Note that this is an extreme example. When the suspect connector is on port 2 in time domain (Figure 24) the characteristics of the first connector and the board can be easily seen. When the bad connector is on port one (Figure 25) the first discontinuity masks all of the following information. There is also a second effect from the suckout which is the frequency domain information is lost for the frequency range of the suckout and is not available for the TDR calculation.

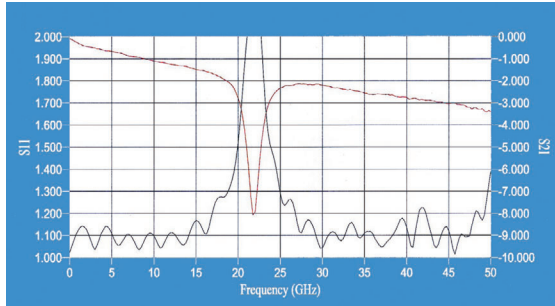


Figure 23: S-Parameter of a Failed Connector on Board

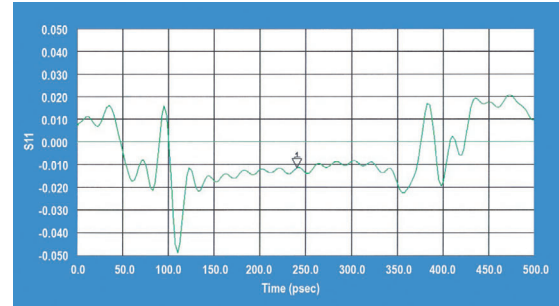


Figure 26: Minimum Window Data

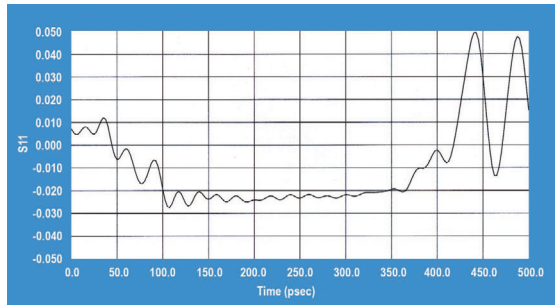


Figure 24: TDR Where the Failed Connector is on Port 2

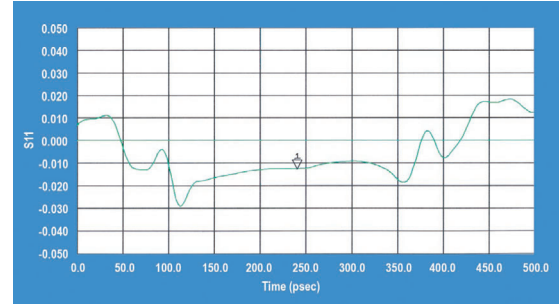


Figure 27: Normal Window Data

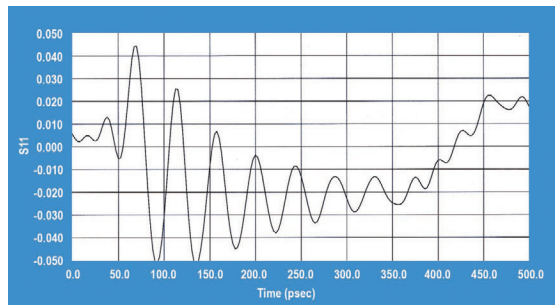


Figure 25: TDR Where the Failed Connector is on Port 1

Windowing

The options for windowing are minimum, normal, and maximum. For the purpose of looking at discontinuities in detail that are close to 50 ohms the minimum window is the best choice. To demonstrate the effect data for the same board is shown with a minimum window (Figure 26) and a normal window (Figure 27).

Windowing is necessary because of discontinuities in the mathematics of performing an inverse Fourier transform. The trade-off in windowing is between resolution and dynamic range. Since the important information is in the detail of the discontinuity, which requires a high degree of resolution, a minimum window is chosen.

Conclusion

This paper outlined the principles of TDR measurements as it relates to measuring discontinuities, showed an example of how to optimize a board, and explained the limitations of such measurements. When used properly TDR measurements can be a very helpful tool in transmission line design. When the results are misinterpreted it can be detrimental to transmission line design. Transmission line designers are encouraged, especially when a coax to connector transition is involved, to start using TDR measurements to help in optimizing designs. ■

References:

- [1] Bill Rosas, Optimizing Test Boards for 50 GHz End Launch Connectors: Grounded Coplanar Launches and Through Lines on 30 mil Rogers R04350 with Comparison to Microstrip, www.southwestmicrowave.com
- [2] National Instruments Tutorial, Selecting Switch Bandwidth, from the NI Development Zone <http://zone.ni.com>
- [3] Agilent Application Note 1287-12, Time Domain Analysis Using a Network Analyzer
- [4] Anritsu Application Note, Time Domain for Vector Network Analyzers