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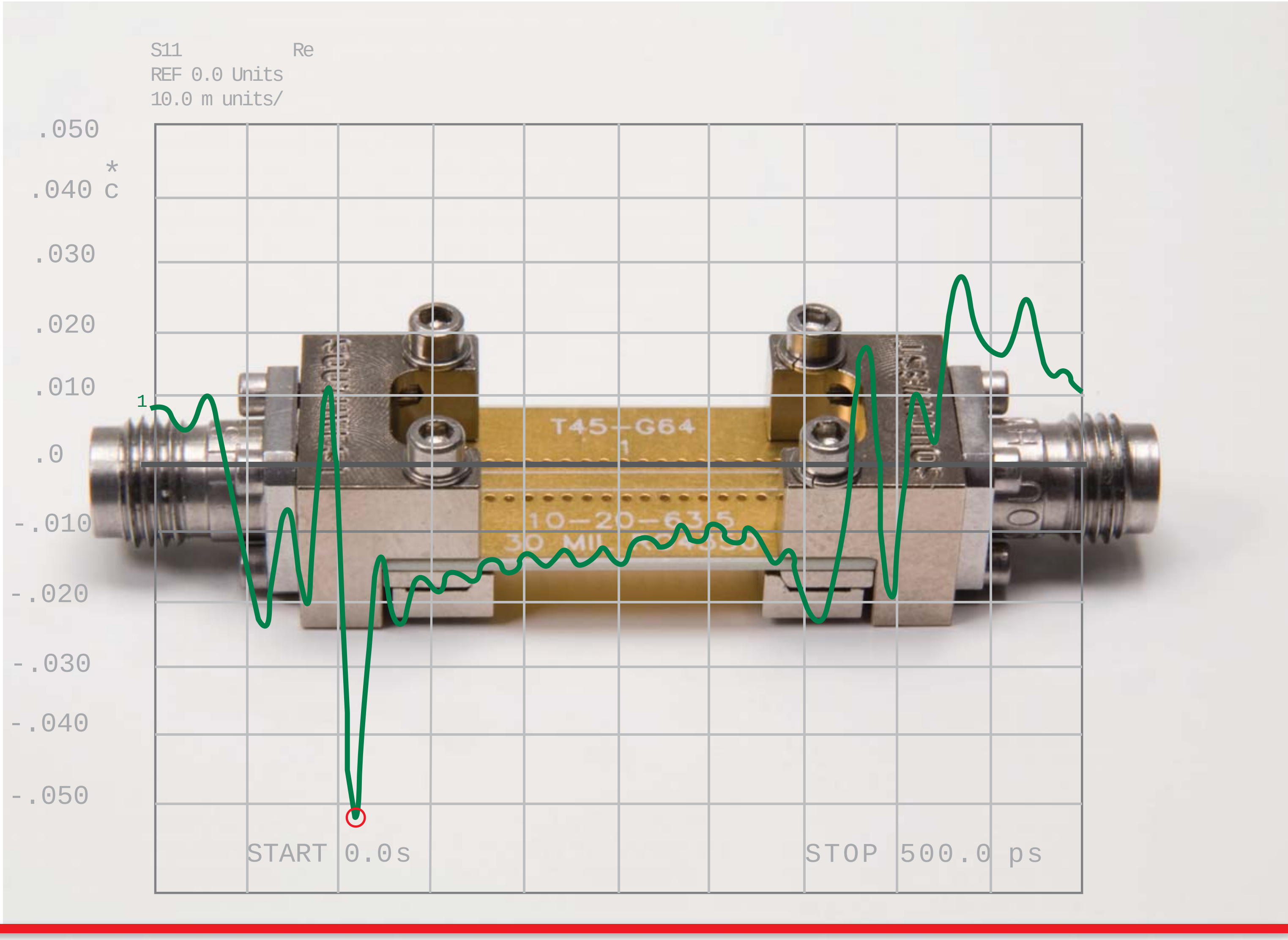
Utilizing Time Domain (TDR) Test Methods

For Maximizing Microwave Board Performance



Southwest Microwave, Inc.

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Utilizing Time Domain (TDR) Test Methods

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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 discusses 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.

What is TDR?

True time domain measurements are made with a pulse generator and an oscilloscope. The 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 of the measurement. The impedance imformation is based on the DC component of the input signal.

Reflections displayed represent discontinuities due to a change in the impedance along a transmission line. The magnitude of the impedance of the discontinuity determines the magnitude of the reflection.

Zero units represents the characteristic impedance of the line, typically 50 ohms.

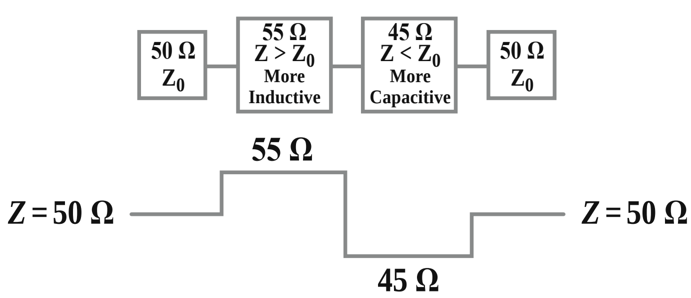
The direction of the reflection on the display, either positive or negative, is determined by whether the impedance that caused the reflection is inductive or capacitive. The impedance formula for a transmission line is:

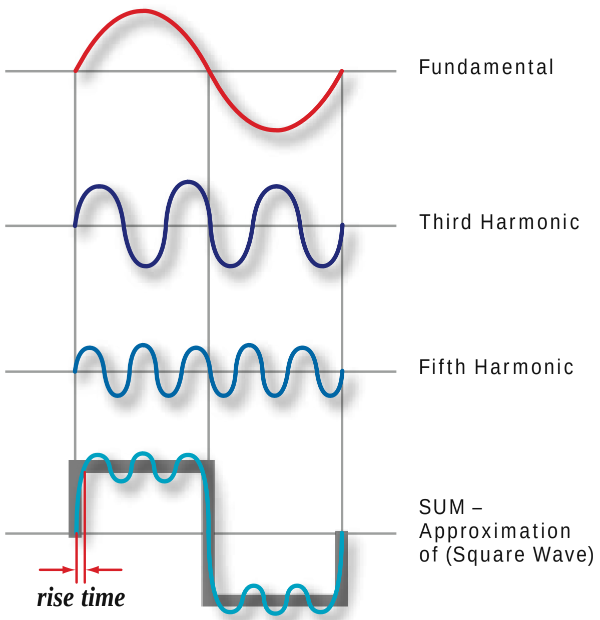
$$Z = \sqrt{\frac{L}{C}}$$

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.

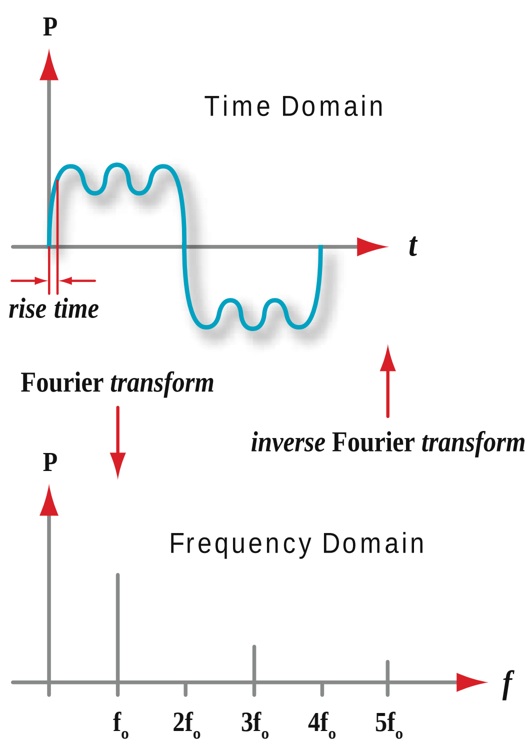
An example transmission line and the corresponding ideal TDR response is shown below. It starts with a 50 ohm characteristic impedance then jumps to 55 ohms (more inductive) then dips to 45 ohms (more capacitive) then returns to the 50 ohm characteristic impedance.

Example Transmission Line and TDR Response





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



Relationship Between Frequency Domain and Time Domain.

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

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

First Three Terms:

$$y = \frac{4}{\pi}\left[\sin(2\pi f t) + \tfrac{1}{3}\sin(6\pi f t) + \tfrac{1}{5}\sin(10\pi f t) + \ldots\right]$$

There are no true square waves in electronics. 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.

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.

Microwave synthesizers do not have a DC signal. The start sweep frequency is used to extrapolate the DC component. The DC component is what is used to determine the impedance. So the lower the start frequency the more accurate the impedance measurement as long as the start frequency stays stable.

Bandwidth vs. Risetime

In frequency domain the highest frequency 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

$$BW = \frac{.35}{t_r}$$

Example:

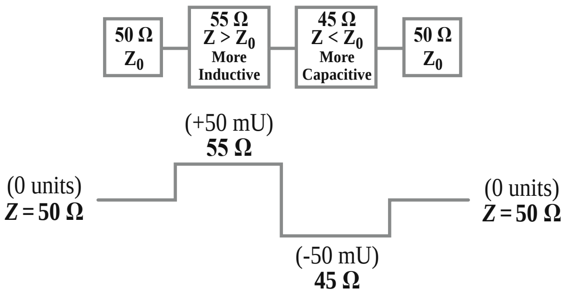
$$t_r = 7 \text{ psec}$$

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

Real Units

Real units are on a logarithmic scale normalizing a short (zero impedance) to minus one and an open (infinite impedance) to plus one with the nominal impedance being zero. In the case of a network analyzer the nominal impedance is 50 ohms and is set by the calibration standard. The formula for impedance to real units is:

$$\text{Real Units (RU)} = \frac{\ln(Z/Z_0)}{2}$$



The scale can be assumed linear close to zero with 10 milli-units approximating an ohm. The transmission line shown on the left is the same shown previously. It starts with a 50 ohm characteristic impedance than jumps to 55 ohms (more inductive) then dips to 45 ohms (more capacitive) then returns to the 50 ohm characteristic impedance. The real unit values are shown on the TDR response for this line with +50 milli-units equaling 55 ohms, -50 milli-units equaling 45 ohms, and zero units equaling 50 ohms.

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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.

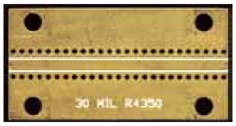
TDR Set-up

The measurement channel should be S_{11} The TDR settings 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

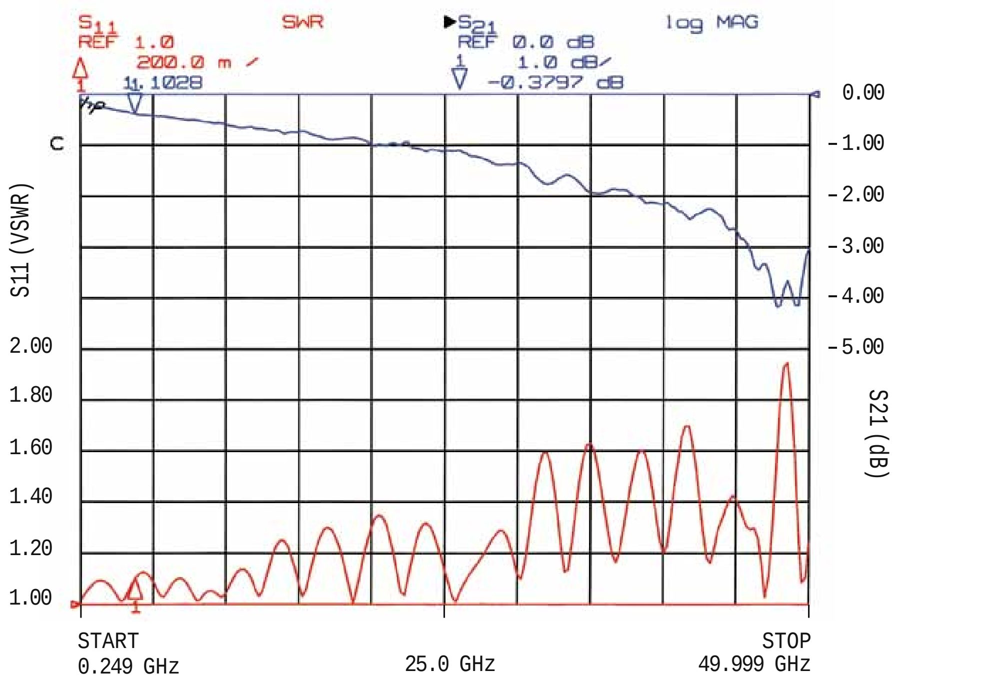
To demonstrate the usefulness of a TDR in board transition designs, the following example will step through the analysis of an actual design. This example is a 1 inch test board fabricated out of 30 mil thick Rogers RO4350 material for 2.4 mm end launch connectors.

The board has a grounded coplanar structure and this is tested through 50 GHz. Southwest Microwave's Standard Format of S-Parameter Data is S_{11} on the bottom of the graph in VSWR with scale of 0.2 per division, and S_{21} on the top of the graph in Log Mag with a scale of 1 dB per division.

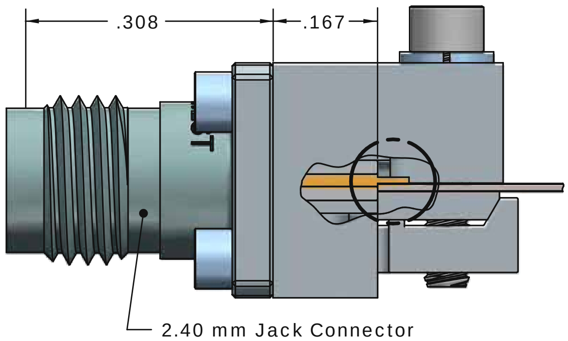


1" Test Board
Trace = 0.045"
Ground = 0.064"
Via Size = 0.020"
Via Spacing = 0.040"
Via Rows = 0.112"

End Launch Connectors mounted on a test board.

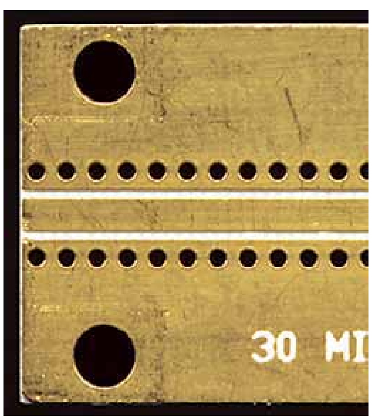


Test data original 30 mil coplanar test board.



Calculation of Electrical Lengths

- Connector is .308” and the dielectric is mostly air ⟶ 26 psec
- Launch pin is .167” and the dielectric is PTFE ⟶ 20 psec
- Total length to discontinuity is roughly (26+20) x 2 = 92 psec



Test Board
30 mil coplanar test board.

Calculating Electrical Lengths

To interpret the TDR plot the electrical lengths of each section need to be calculated.

Formula for Calculating Electrical Lengths In Time

$$t = \frac{l}{c}\sqrt{\epsilon_r}$$

c is the speed of light

The connector is .308” and it has an air dielectric. This calculates to an electrical length of 26 picoseconds (psec).

$$t = \frac{.308\ in}{.0118\ in/psec} \approx 26\ psec$$

The actual electrical length of the connector is slightly longer because it is not all air. There is a plastic bead that captures the center conductor.

The launch pin is .167 in and the dielectric is Teflon® which has a dielectric constant of 2. This calculates to an electrical length of 20 psec.

$$t = \frac{.167\ in}{.0118\ in/psec} \times \sqrt{2} = 20\ psec$$

The total electrical distance displayed on the VNA is twice the combined distance since the return distance is included.

$$t = (26\ psec + 20\ psec) \times 2 \approx 92\ psec$$

Analyzing the TDR Plot

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 red circled point is about -50 milli-units which converts to 45 ohms. The time scale is 50 psec per division so this point is just over 100 psec. Looking at the physical structure this discontinuity can be explained by the pin sitting on the trace, so it is assumed to be real.

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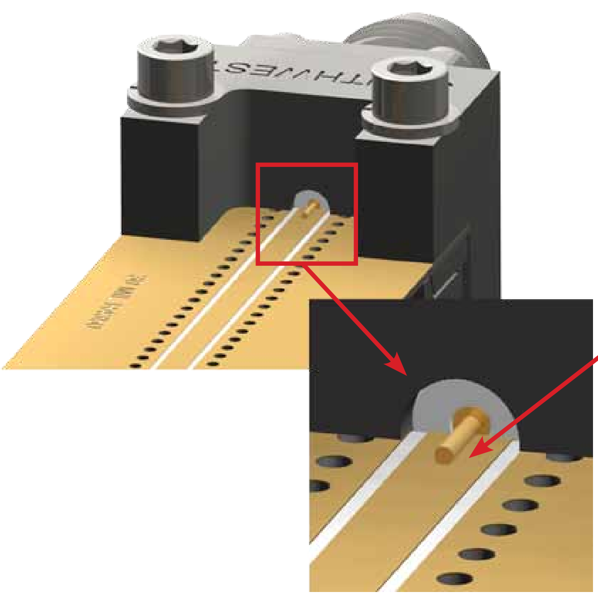
Inductive Point:

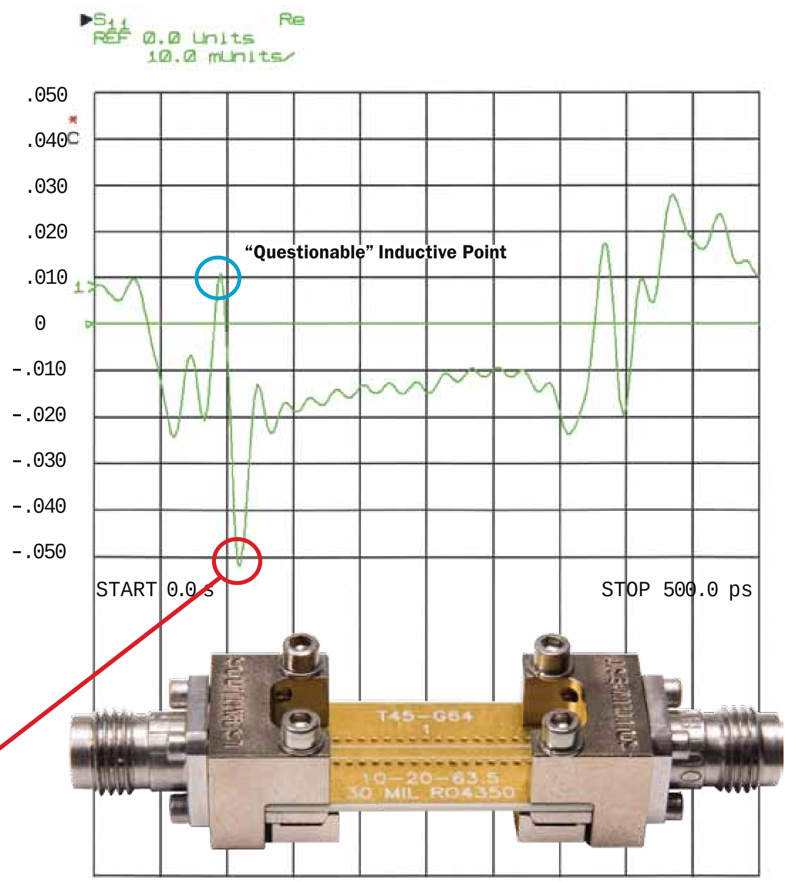
VNA generated TDR graphs are not direct measurements so errors can occur in the computation. Windowing is used to reduce the effects of these computational errors from anomalies in the reverse Fourier transform. With this test board there is nothing in the structure that corresponds to the inductive spike circled in blue.

To confirm that this was a “questionable” inductive point, capacitance was added by extending the Teflon out over the pin on the board. The inductive spike did not change which indicates it is not an accurate point in the TDR. Changing the windowing to normal greatly reduces the spike as seen in the windowing section of this paper. Also, the simulated TDR from time domain based simulation software does not show it either.

Time Domain (TDR) Test Data

The TDR data is in real units over time/distance. It shows the discontinuity at the launch and the impedance of the board. The discontinuity of the launch is a capacitive spike circled in red of a little lower than -50 milli-units. The board impedance is the long section in the middle varying from -20 milli-units to -10 milli-units.





TDR of original coplanar test board.

How to Optimize a Transition Using TDR

3-D Simulation

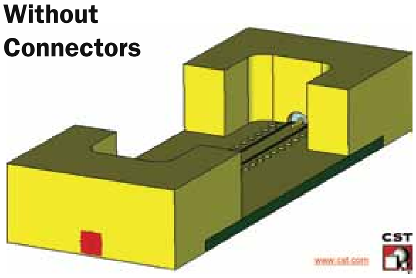
3-D electromagnetic simulation can be used to predict the results of these types of structures. Then changes can be made and the results of the changes can be viewed without having to fabricate and test actual hardware. Decent correlation of the known performance of this test board was achieved with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

CST MWS Model

The 3-D simulation model is created by looking only at the transition blocks and the test board. Simulation results verify that the biggest discontinuity in the transmission line is the transition from coax to PCB.

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

CST MWS Model Without Connectors

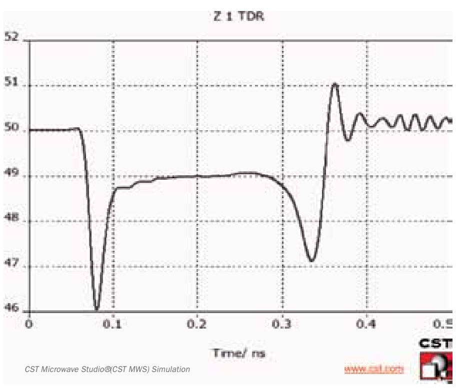


Simulation Results

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.

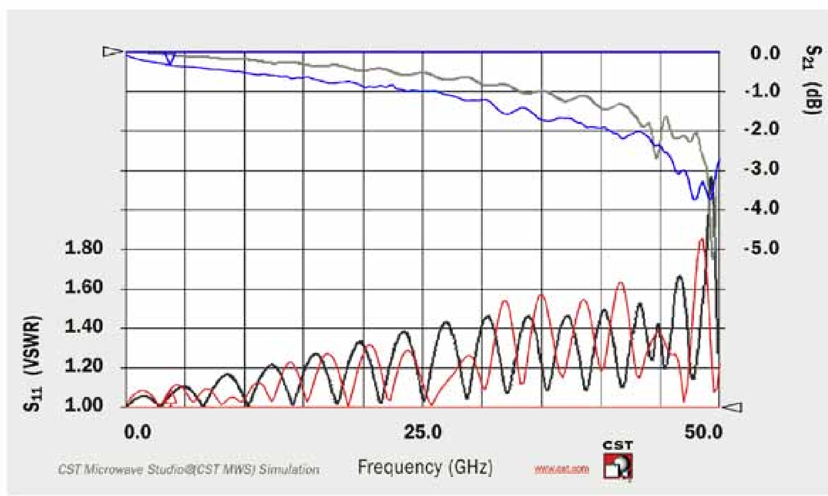
Simulated S-Parameter data matches very well with measured data.

TDR



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.

Original Test Board Simulation & Actual Test Data S-Parameter Data / VSWR



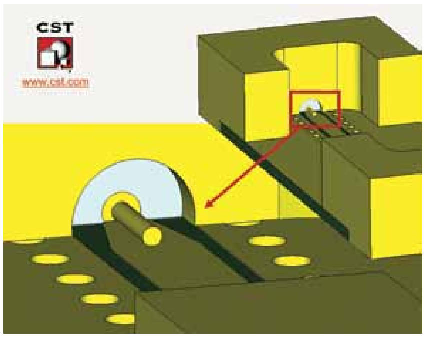
Simulation of original test board (shown in black & gray), **compared to actual measured data** (shown in red & blue).

Maximizing the Test Board Performance

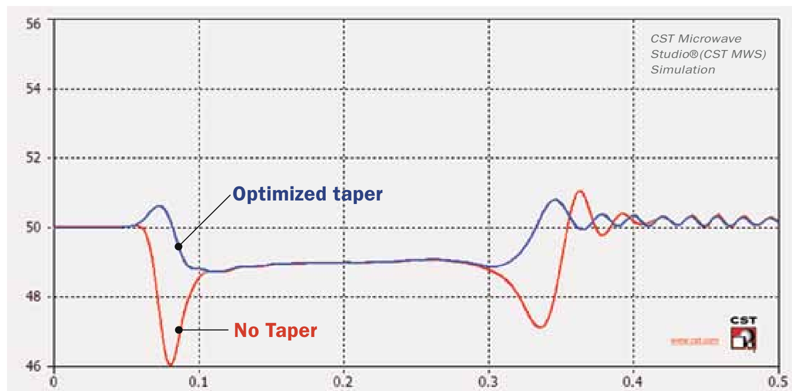
Inductance needs to be added to the board layout to offset the added capacitance of the launch pin. This is done with a taper and the taper is designed such that boards can be modified with an X-Acto® knife for those that do not have a simulation tool.

The optimized taper design was developed using CST Microwave Studio's optimization routine. The simulation results show the capacitive dip is reduced producing excellent results for S_{11}, much better than could be realized in practice and the insertion loss is very smooth up to the normal 45 GHz glitch always seen.

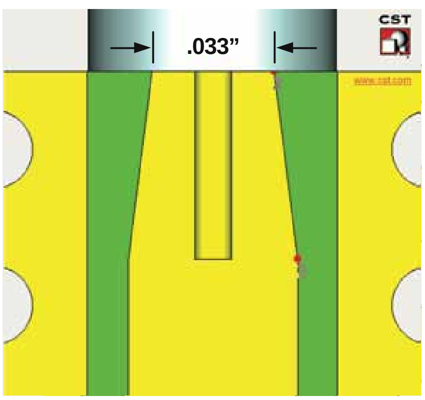
Taper



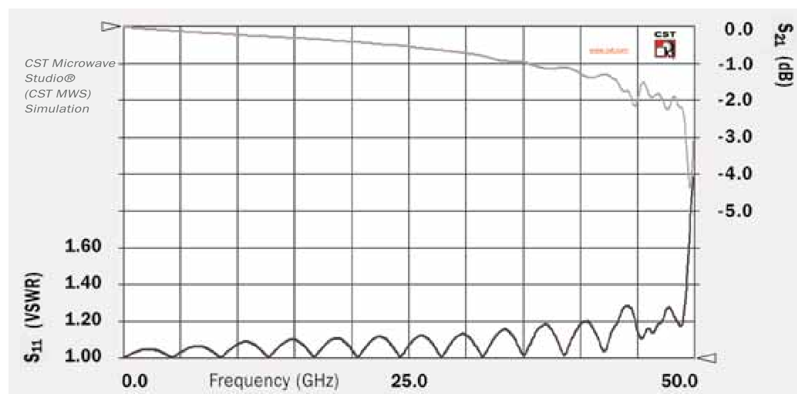
Simulated TDR Comparison: Optimized taper No Taper TDR

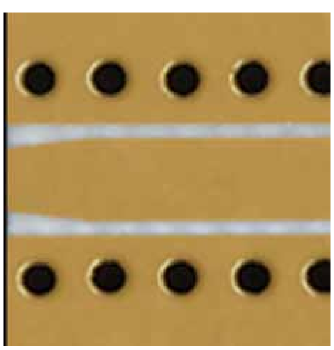


Optimized Taper

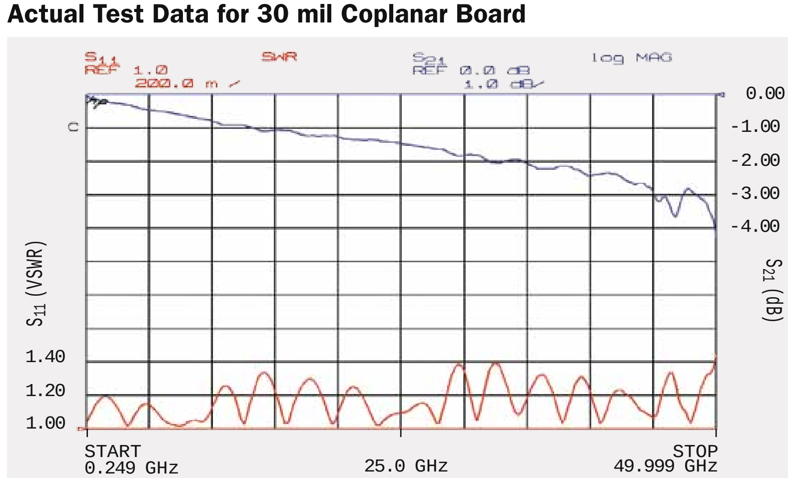


Optimized taper Simulated S-Parameter Data / VSWR





Actual Test Data for 30 mil Coplanar Board



Enlarged View of Coplanar Test Board Showing Optimized Taper

Overview of Agilent 8510C Workstation

Test Set-up Critical for Useful TDR Results

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

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

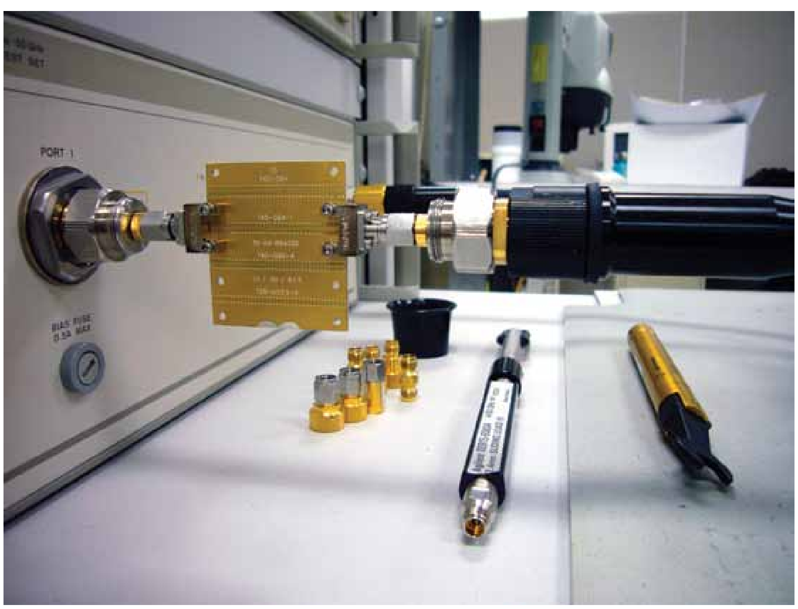
The higher the frequency range the better the resolution and there is a minimum number of points needed depending on the electrical length of the device under test. TDR measurements are set up as low pass with step response in real units with a minimum window. The scale is 10 milli-units per division.

Port Configuration of Agilent 8510C Workstation with a Single Cable

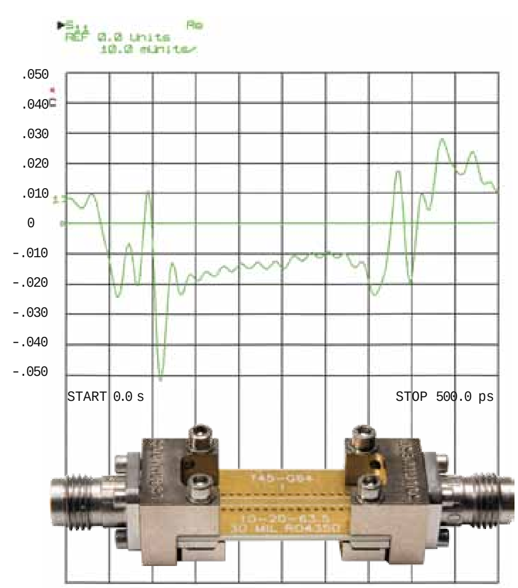
Agilent 8510C

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.



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



Overview of Anritsu 37297D Workstation

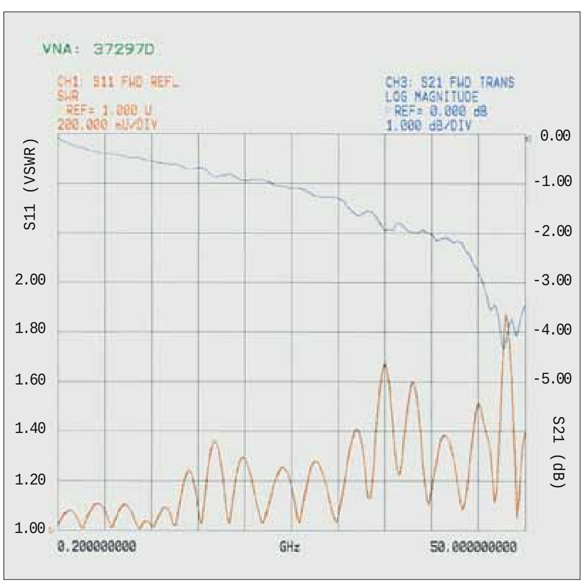
Differences Using Anritsu Equipment

Anritsu VNA's 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 low pass with step response, real units, 10 milli-units per division, but the windowing is called "rectangular" instead of "minimum".

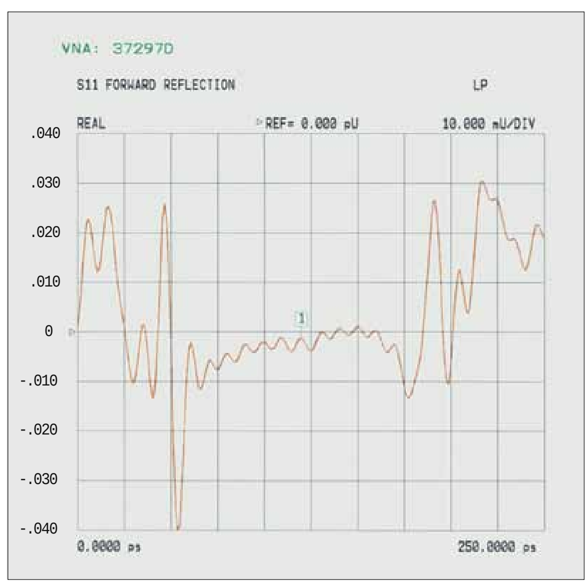
Device Under Test Connected to Port 1

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: low pass with step response, real units, 10 milli-units per division
- Windowing is "rectangular" instead of "minimum".



Anritsu S_{11} Test Data on the Anritsu 37297D



Anritsu TDR Test Data on the Anritsu 37297D

Smith Chart Display to Show Impedance

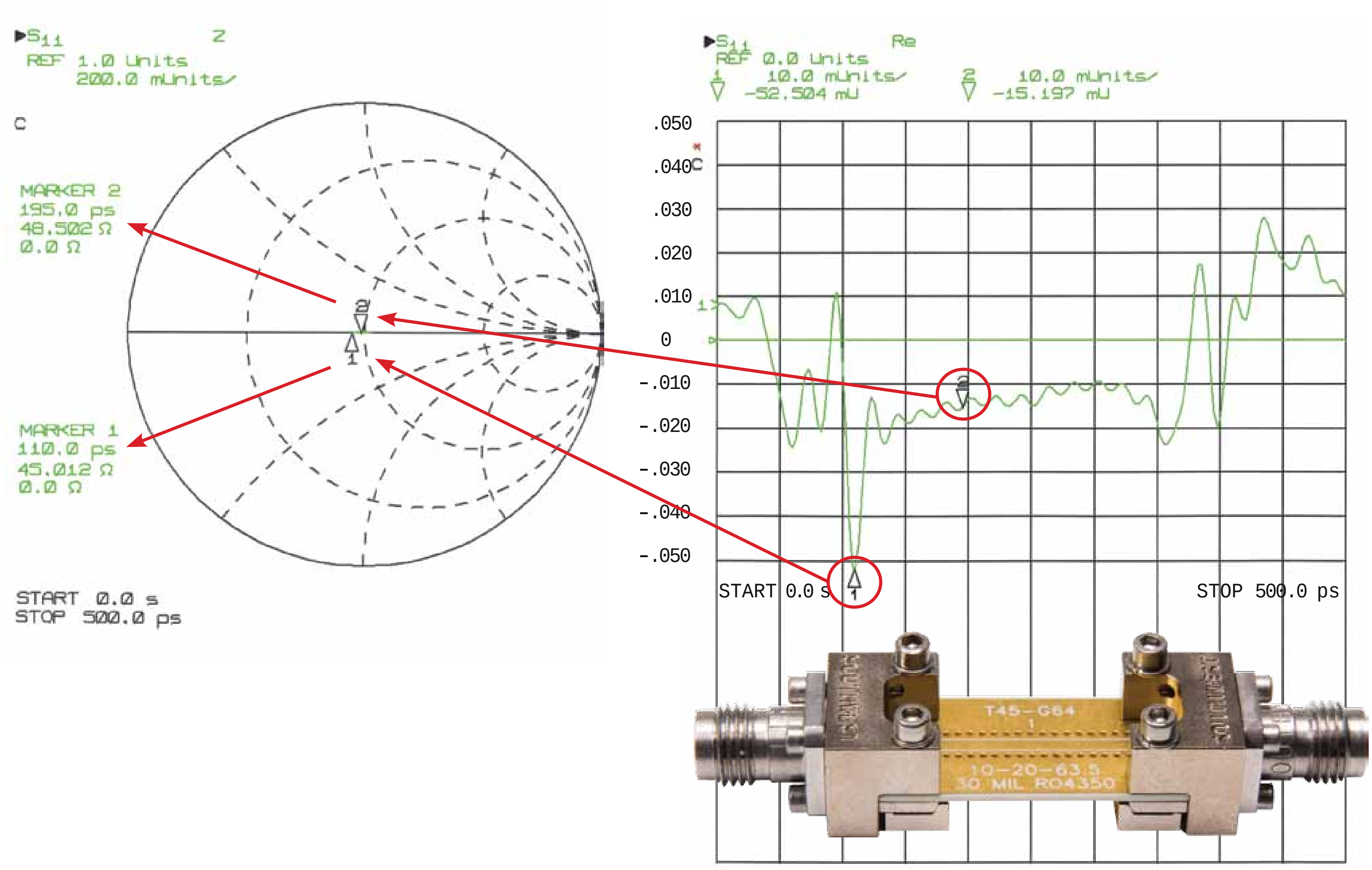
Using a Smith Chart can give the impedance value at a single point or multiple points. The formula for the conversion between real units and impedance is:

$$Z = e^{(RU^{*} x 2)} x Z_0$$

** RU is Real Units*

To display the impedance on a Smith Chart, first turn on a marker or markers on the TDR display. Move them to the points to be converted. Then change the display to Smith Chart and the impedance value will be displayed on the Smith Chart markers.

For an Anritsu VNA the impedance Smith Chart option should be chosen.



TDR comparison to Smith Chart of coplanar test board.

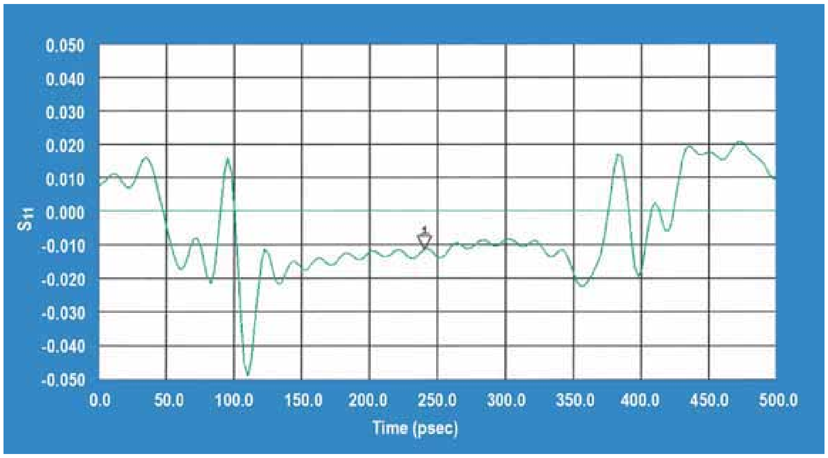
Interpretation of Results: Assumptions/Caveats

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, sometimes 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.

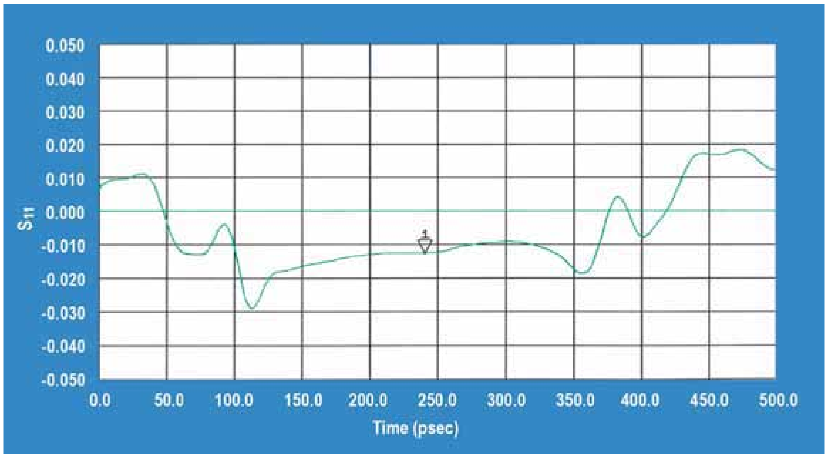
Windowing

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 and a normal window. In both plots t he frequency sweep is to 50 GHz in 201 points.

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.



Minimum Window Data



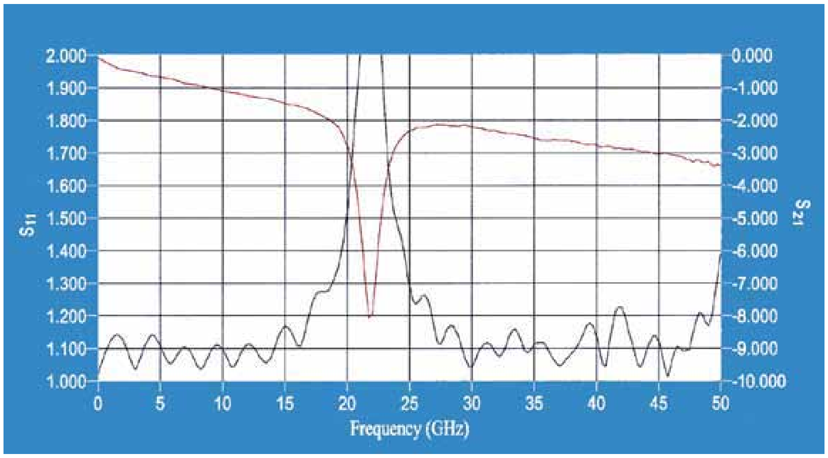
Normal Window Data

Masking

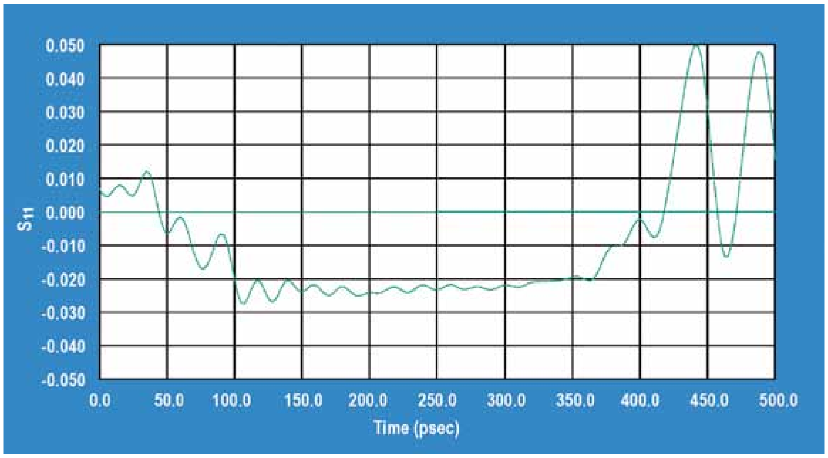
A large discontinuity will "mask" the rest of the data. This is because the first discontinuity will affect any energy that gets past it and then affect it again on the return trip.

The first plot is a frequency domain measurement where a bad connector on a test board is creating what is called a "suckout". Note that this is an extreme example. When the suspect connector is on port 2 in time domain, the characteristics of the first connector and the board can be easily seen. When the bad connector is on port 1, the first discontinuity masks all of the following information.

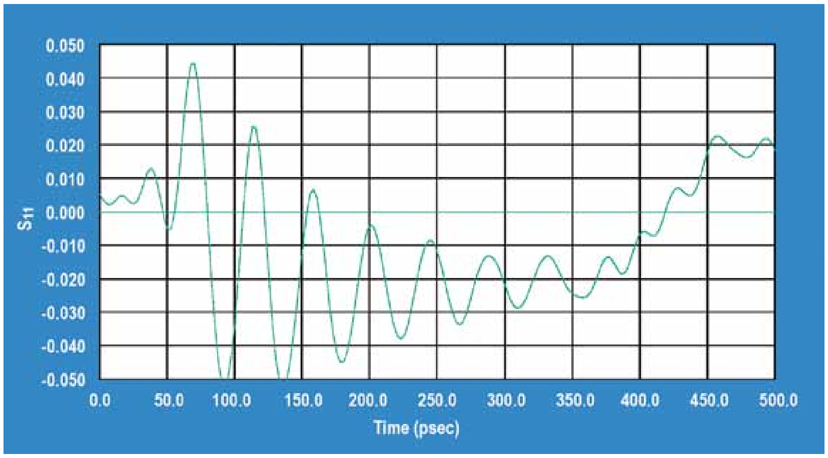
There is also a second effect from the suckout which is the frequency domain information is lost for the frequency range of the "suckout" and is not available for the TDR calculation.



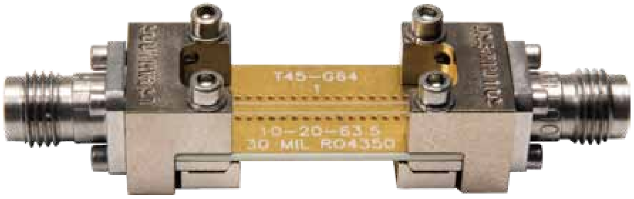
S-parameters of a failed connector on a board

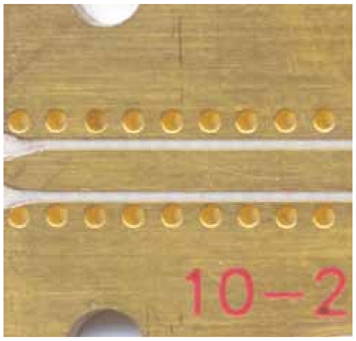


TDR where the failed connector is on port 2

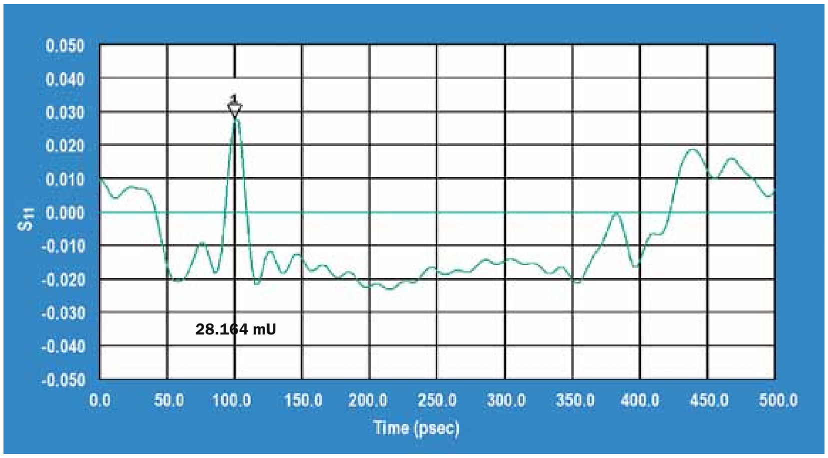


TDR were the failed connector is on port 1





This test board was modified with an X-Acto knife to introduce a large discontinuity.



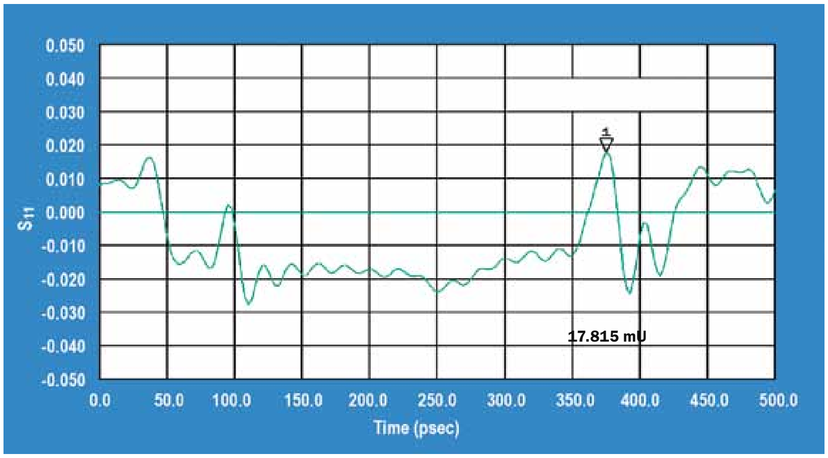
TDR where board end A is on port 1

Masking

When measuring a TDR through significant loss, accuracy will be reduced.

One of the test boards was modified using the X-Acto knife method to introduce a large discontinuity. The end of the board with the discontinuity is the "A" side.

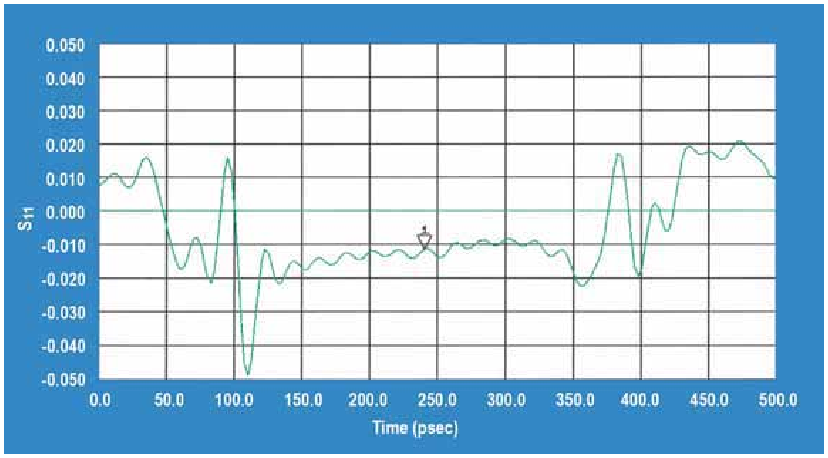
The discontinuity on the connector A side of the board, when connected to port 1, measures 28.2 milli-units which is 52.9 ohms. When the board is turned around and connector A is on port 2, then the same discontinuity is measured as 17.8 milli-units which is 51.8 ohms. The more accurate measurement is when connector A is on port 1.



TDR where board end A is on port 2

Resolution

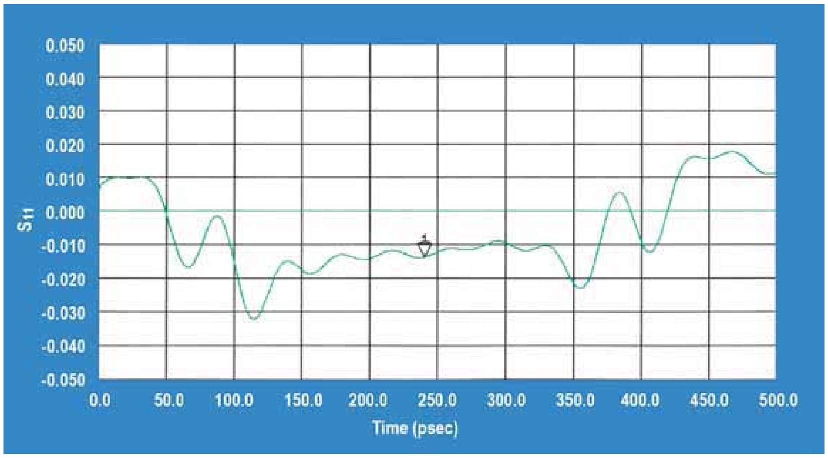
The resolution of a TDR is frequency dependant; the higher the frequency the more resolution. Resolution can also be compromised if there are not enough data points in the sweep. Shown is a 50 GHz sweep with 201 points.



High Frequency Resolution (50 GHz, 201 points, 250 MHz start fequency)

Resolution (Low Frequency)

A low frequency graph 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.

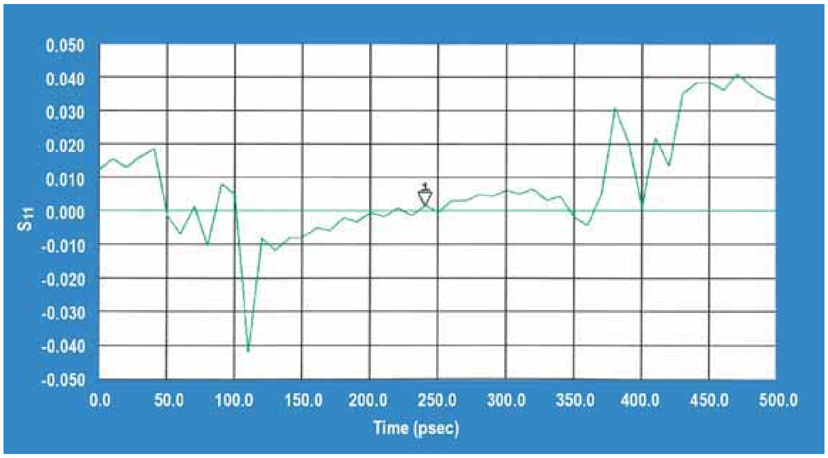


Low Frequency Resolution (27 GHz, 201 points, 135 MHz start frequency)

Resolution (Number of Points)

A low number of points graph 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.

There is also an accuracy issue when the number of points are reduced. This is because the DC term is not extrapolated as accurately with a higher start frequency. Remember that it is also important that the start frequency is stable.



Too Few Data Points Resolution (50 GHz, 51 points, 1 GHz start frequency)

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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 after that. 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.

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:

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[3] Agilent Application Note 1287-12, Time Domain Analysis Using a Network Analyzer

[4] Anritsu Application Note, Time Domain for Vector Network Analyzers

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