TIME DOMAIN ANALYSIS WITH COPPER MOUNTAIN TECHNOLOGIES VECTOR NETWORK ANALYZERS (VNA)

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09/20/2019

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INTRODUCTION

A Vector Network Analyzer (VNA) natively measures complex S-parameters of a device under test (DUT) in the frequency domain mode by sweeping across various frequency points. While there is an exhaustive list of measurements that can be accomplished in the standard frequency domain mode – using the advanced inverse Chirp z-transformation, the measurements can also be simultaneously analyzed in the time domain mode. This gives the added advantage where the two fundamental modes of analysis can be performed by one single instrument.

A VNA with its highly accurate vector error correction method can precisely locate the mismatches just like a traditional Time Domain Reflectometer (TDR) would. Although both instruments provide frequency and time domain using Fourier transform, they work differently in terms of the principle operation. Unlike a TDR where it sends a step or an impulse down the transmission line and compares the reflected signal with a wideband oscilloscope, a VNA uses narrowband tuned receivers to compare the swept frequency signal, thereby paving way to achieve better signal to noise ratio. Creating a higher dynamic range, which is useful for a lot of measurements, even in the time domain mode.

For an RF/Microwave engineer, time domain measurements are primarily useful in identifying a device's behavior at specific locations. And more recently, with the increasing necessity of high-speed applications, VNAs are also gaining popularity with digital engineers for signal integrity tests.

Note: All Copper Mountain Technologies' VNAs, except the compact M Series, come with time domain and gating as a standard feature in the VNA application software.

BRIEF THEORY

Fourier transform is a powerful tool which makes the frequency and time domain transformations possible. These transformations are performed by analyzing the impulse and step responses of a network. Various fast Fourier transform (FFT) algorithms are used in test and measurement instruments due to its superior computation times when compared to discrete Fourier transform (DFT). However, as the VNA measures discrete magnitude and phase of the DUT over a finite frequency range, there are some limitations on the transformations that can be applied. So, a proprietary chirp z algorithm is used. The advantage of using chirp z is that it offers greater flexibility in evaluating the z-transform along contours other than the unit circle, as the input and output samples do not have to be the same. This essentially allows the user to zoom into the desired area on the time domain axis.

From [1], for a given *N*-sample sequence, the chirp z-transform is defined as:

$$X(k) = \sum_{n=0}^{N-1} x[n]\,(A.W^{-k})^{-n}$$

Where *X(k)* is the transformed response for the given *N*-sample sequence *x[n]* sampled in *M* points ($0 \leq k \leq M-1$). Here *A* and *W* are arbitrary complex numbers defined as:

$$A = A_0 e^{i2\pi\theta_0}$$

$$W = W_0 e^{-j2\pi\varphi_0}$$

Where A_0 is the starting radius, θ_0 is the starting angle and φ_0 is the angular step size. The rate at which the contour spirals in or out from the circle of radius A_0 is set by the constant W_0. The $A\ W^{-k}$ term configures the contour at which the z-transform is defined.

Besides this, there are additional functions to be considered prior to applying transformation such as: low pass (where the DC and negative frequencies are extrapolated to simulate TDR) & bandpass modes (for band limited DUTs) and windowing (to truncate the signal) to name a few. Users can adjust these settings to best suit their application. As the focus of this application note is not to delve into the underlying algorithm, the next section shows how these, and other settings affect the time domain transformations in a VNA.

SETTINGS

Time domain transformations are trace wise operations performed on an active trace when the sweep type is set to linear. To accomplish the desired time domain measurements for various applications, appropriate settings must be used.

Frequency Domain Settings

Frequency Span

Resolution in time domain is inversely proportional to the frequency span of the VNA setting. So, the wider the frequency, the better the resolution is. In addition to the frequency span settings, the window settings (discussed later) also determine the resolution in time domain mode:

$$Resolution\ (in\ distance)\ \approx \frac{V_p * C}{2 * (Fmax - Fmin)}$$

Where V_p is the velocity factor of the transmission line

C is the speed of light

$Fmax\ \&\ Fmin$ are the maximum and minimum frequency from the VNA

In general, to achieve higher resolution, the full range of the VNA must be utilized even if the frequencies are outside the DUT's working range. This is valid as long as the DUT is not band limiting such as filters or waveguides.

Points

Range in time domain, is directly proportional to the number of frequency points and inversely proportional to the frequency step size of the VNA setting. So, to measure longer distances, it is necessary to set many frequency points. Here is the equation to calculate the alias-free range (to avoid repeated response):

$$Distance\ (one\ way) = \frac{V_p * C}{2 * \Delta f}$$

Where V_p is the velocity factor of the transmission line

C is the speed of light

$$\Delta f\ (frequency\ step\ size) = \frac{Fmax - Fmin}{total\ points - 1}$$

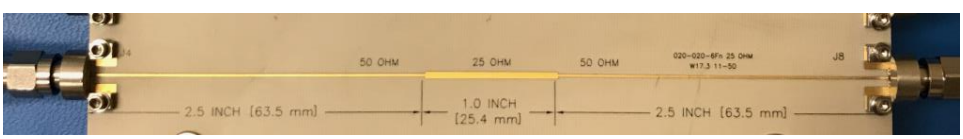
For proper time domain computations, it is always recommended to choose more than adequate frequency points. However, the downside of setting a large number of frequency points is the slower sweep speed.

Time Domain Settings

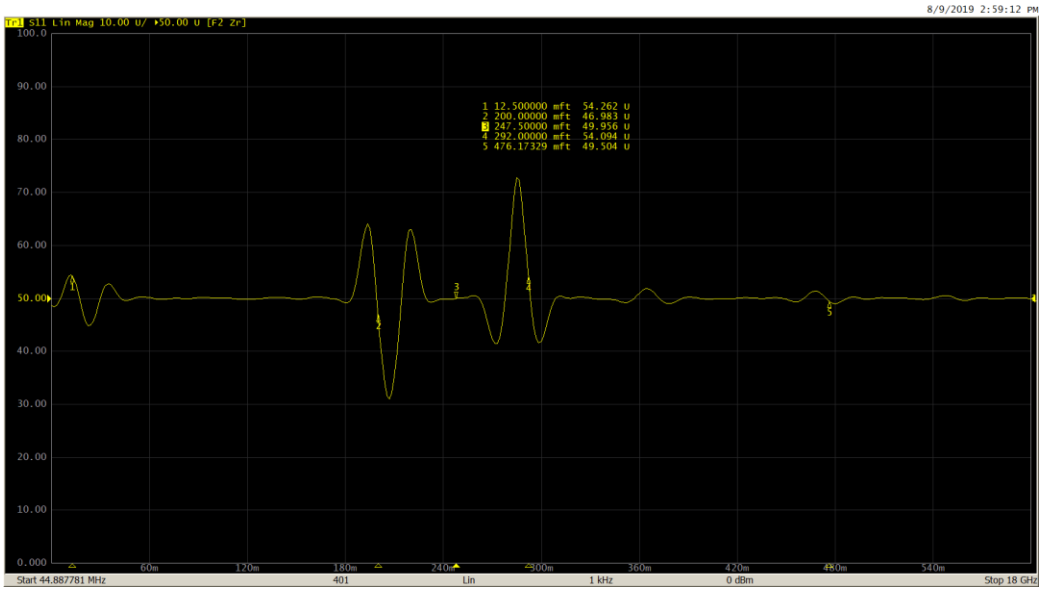
Transformation Type:

A: Bandpass Mode

The bandpass mode is a simpler and generic transformation mode, which simulates the impulse bandpass response. This mode does not require the frequencies to be harmonically related. So, it can be used over any arbitrary frequency range. This is mostly useful for measuring band-limited devices such as filters and waveguides. The disadvantage here is that this mode only allows you to identify locations of mismatches and discontinuities, it does not show if they are capacitive, inductive, or resistive.



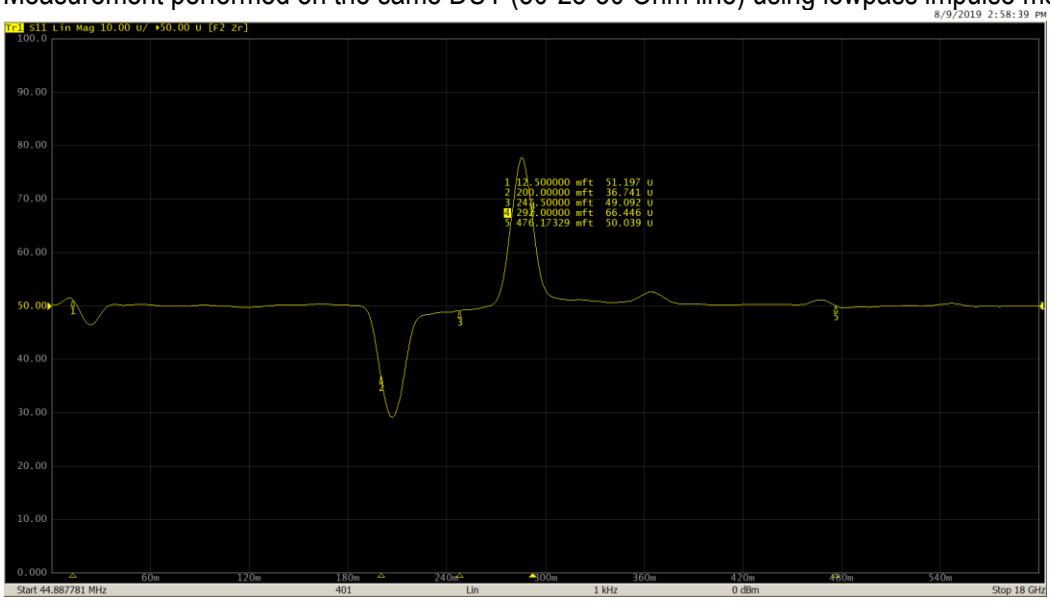
Here is a bandpass mode response for impedance vs. distance on a 50-25-50 Ohm line:



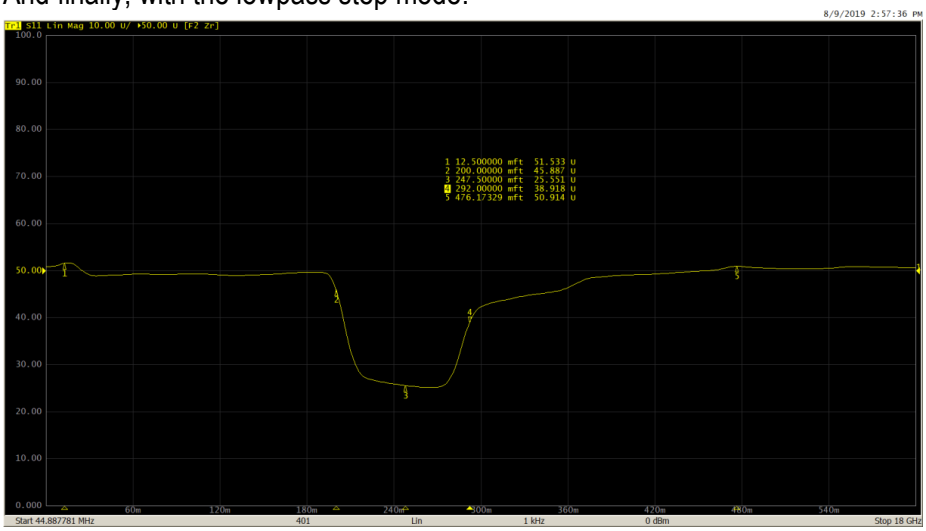
B: Lowpass Mode

The low-pass mode, on the other hand, is useful in determining the type of impedance change present at the mismatch location. This mode simulates lowpass impulse or step responses. In both the low-pass modes, frequencies down to DC are extrapolated to create the harmonic grid necessary for this transformation. Because of this, both step and impulse low-pass modes provide better time domain resolution for a given frequency span than the bandpass mode. In this mode, response to the step and the impulse stimulus contains information describing both, where the mismatch is located, as well as what type of impedance change is present. This mode is suitable for DUTs which go down to DC, such as cables.

Measurement performed on the same DUT (50-25-50 Ohm line) using lowpass impulse mode:



And finally, with the lowpass step mode:



Windowing

In practice, every signal must be finite before processing. So, the input signal must be sampled and truncated before performing time domain transformations. However, this results in spectral leakage at discontinuities. The amount of this leakage is dependent on the amplitude of the discontinuities; which can be adjusted by applying the window function. This is performed by multiplying the time domain signal with a window waveform.

The VNA application uses Kaiser window to perform time domain transformation. The Kaiser window is described by β parameter, which smoothly fine-tunes the window shape from minimum (rectangular) to maximum. The window shape can be fine-tuned or set using the three preprogrammed windows:

- **Minimum** (rectangular);
- **Normal**;
- **Maximum**.

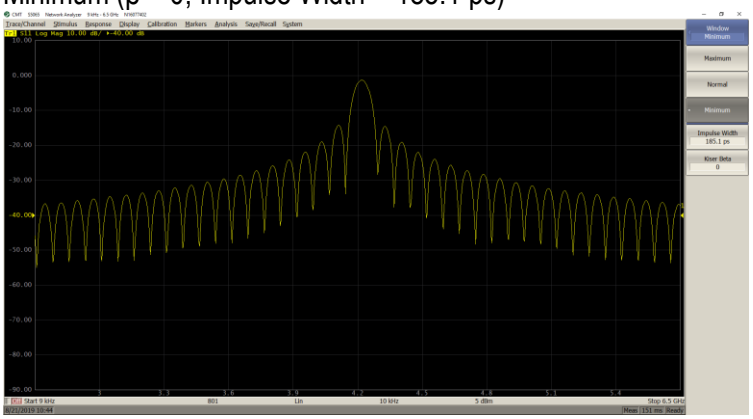
The β values can be adjusted from 0 to 13. 0 corresponds to minimum window, 6 corresponds to normal window, 13 corresponds to maximum window. As the β value increases, it is easy to notice the trade-off between the main-lobe width (or the step rise time in low pass) and the side-lobe level.

Window	Bandpass Impulse		Lowpass Impulse		Lowpass Step	
	Side Lobes Level	Pulse Width	Side Lobes Level	Pulse Width	Side Lobes Level	Edge Width
Minimum	– 13 dB	$\frac{1.2}{Fmax - Fmin}$	– 13 dB	$\frac{0.6}{Fmax - Fmin}$	– 21 dB	$\frac{0.45}{Fmax - Fmin}$
Normal	– 44 dB	$\frac{1.96}{Fmax - Fmin}$	– 44 dB	$\frac{0.98}{Fmax - Fmin}$	– 60 dB	$\frac{0.99}{Fmax - Fmin}$
Maximum	– 75 dB	$\frac{2.78}{Fmax - Fmin}$	– 75 dB	$\frac{1.39}{Fmax - Fmin}$	– 75 dB	$\frac{1.48}{Fmax - Fmin}$

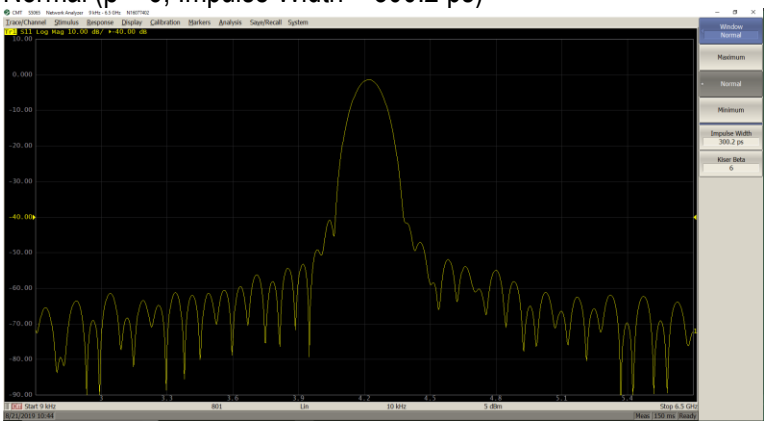
Here are the effects of windowing:

Bandpass Mode:

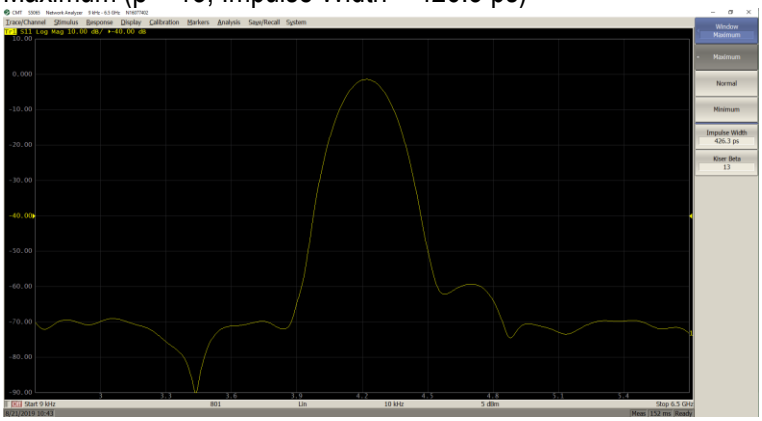
Minimum (β = 0; Impulse Width = 185.1 ps)



Normal (β = 6; Impulse Width = 300.2 ps)

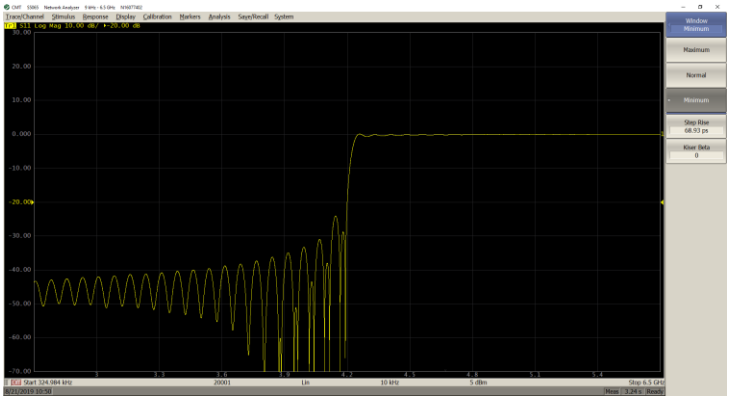


Maximum (β = 13; Impulse Width = 426.3 ps)

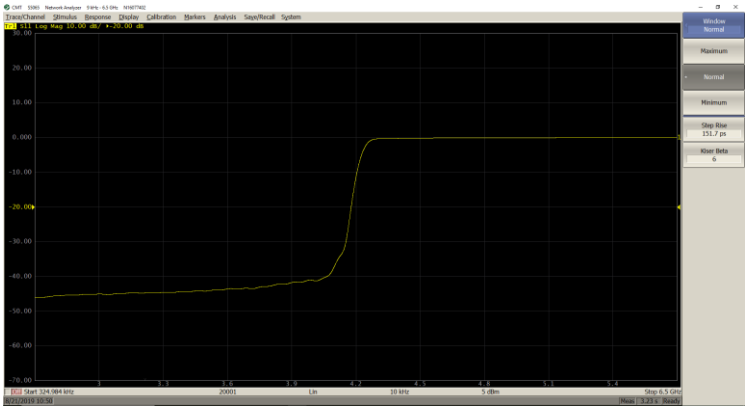


Lowpass step Mode

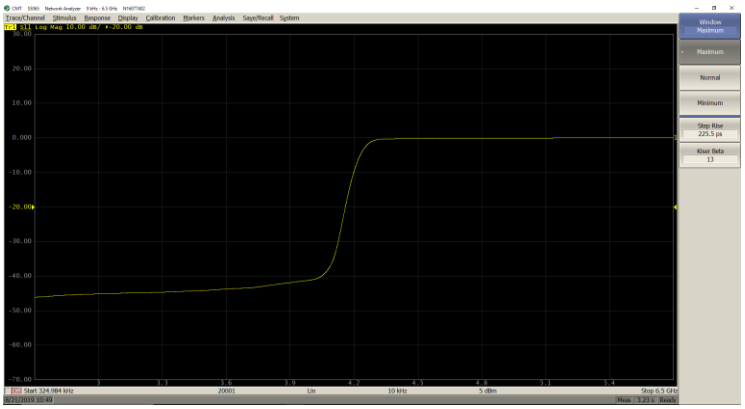
Minimum (β = 0; Step Rise = 68.93 ps)



Normal (β = 6; Step Rise = 151.7 ps)



Maximum (β = 13; Step Rise = 225.5 ps)



Velocity Factor

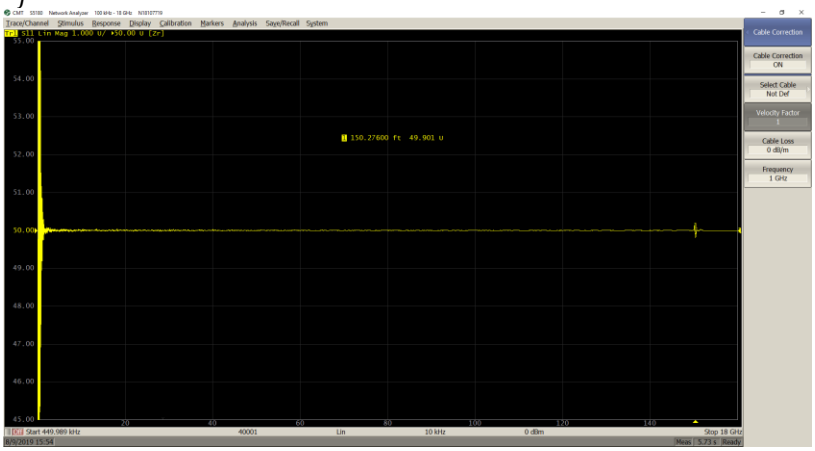
Time and distance are related by velocity. To obtain the accurate mismatch location, it is important to set the right velocity factor of the transmission medium.

By default, the application software assumes it to be equal to 1. But in practice, this can be different depending on the characteristics of the transmission line. If the velocity factor of a transmission line is not known, it can be calculated from the dielectric constant value:

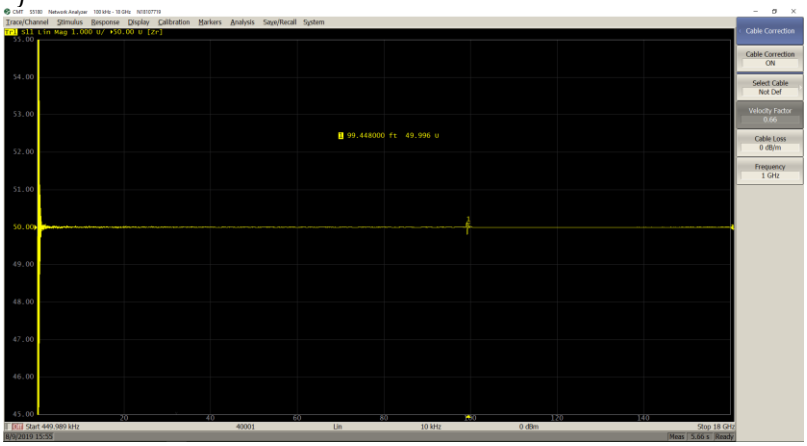
$$V_f = \frac{1}{\sqrt{\varepsilon_r}} \qquad \text{where } \varepsilon_r \text{ is the dielectric constant value}$$

The two measurements below show the impact of entering the proper velocity factor value on a 100 feet cable:

V_f = 1



V_f = 0.66



As seen from the marker values, only by entering the proper velocity factor (0.66 for the cable under test), can the correct length of the cable be seen.

TIME DOMAIN GATING

Time domain gating is another powerful feature in a VNA which mathematically removes the unwanted responses in time domain. The function performs time domain transformation and applies reverse transformation back to frequency domain to the user-defined span in time domain. This function is used to remove the mismatch effects of the fixture devices from the frequency response, if the useful signal and the mismatch signal are separable in time domain.

The function involves two types of time domain gating:

- *bandpass* – removes the response outside the gate span,
- *notch* – removes the response inside the gate span.

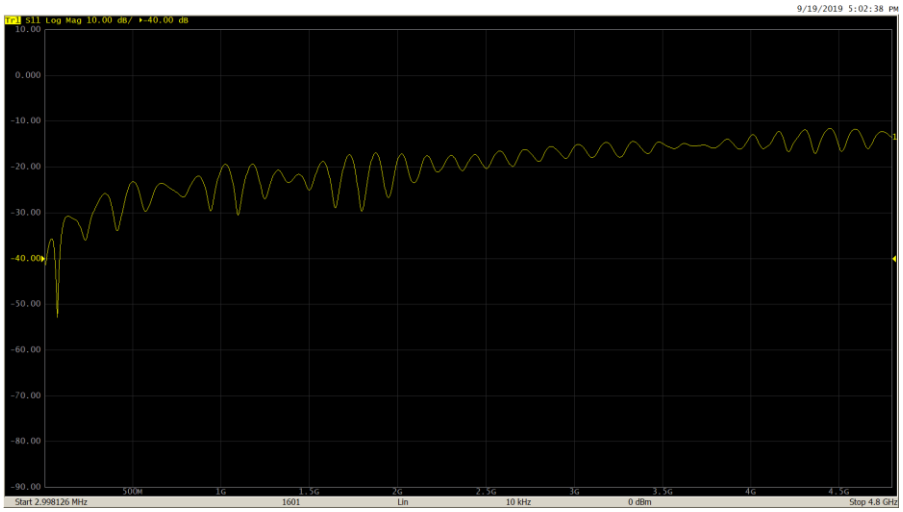
The rectangular window shape in frequency domain leads to spurious sidelobes, due to sharp signal changes at the limits of the window. The following gate shapes are offered to reduce the sidelobes:

- *maximum*;
- *wide;*
- *normal;*
- *minimum.*

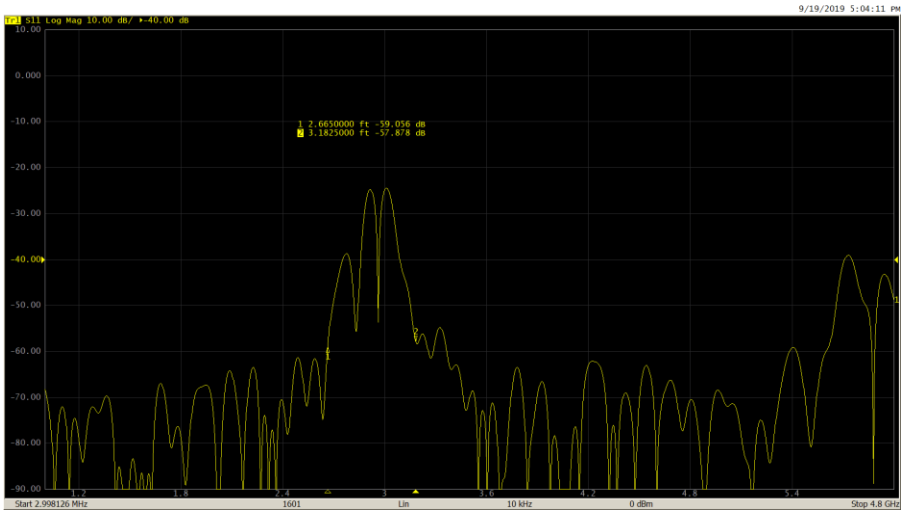
The minimum window has the shape close to rectangular. The maximum window has a more smoothed shape. From minimum to maximum window shape, the sidelobe level increases and the gate resolution reduces. The choice of the window shape is always a trade-off between the gate resolution and the level of spurious sidelobes.

Here is the effect of applying gating on a mismatch in a 50 Ohm cable:

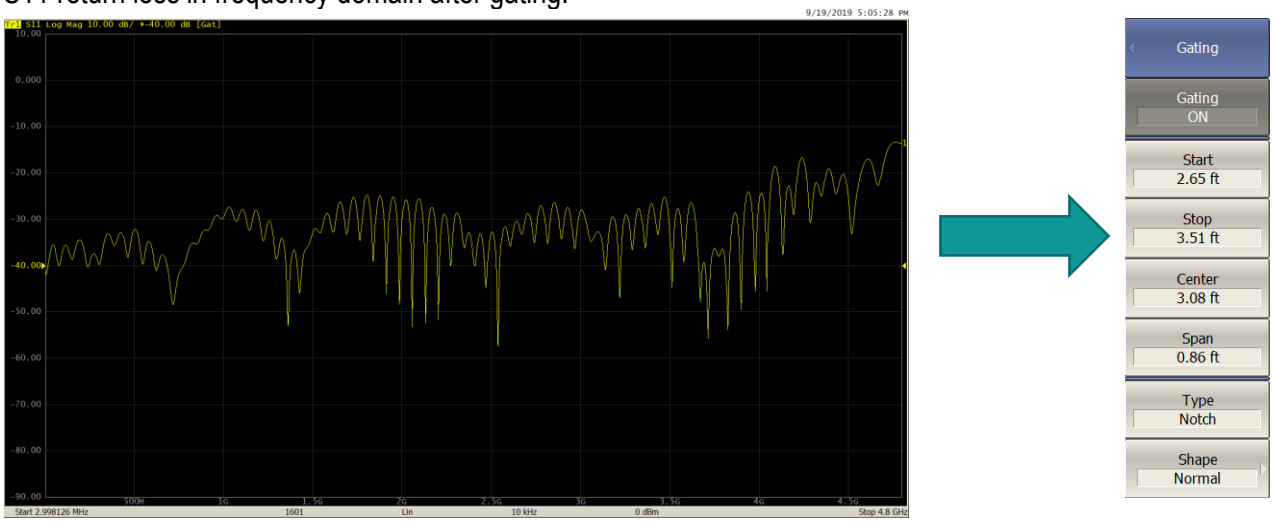
S11 return loss in frequency domain before applying gating:



Response viewed in time domain:



S11 return loss in frequency domain after gating:



After gating out the mismatch using 'Notch' type, as expected, the S11 return loss shows improvement.

ACCURACY CONSIDERATIONS

Due to the intricacies involved in setting up time domain measurements for various applications, the measurement accuracy of a vector network analyzer (VNA) in time domain is not specified. Therefore, these data are not stated in the specifications, since they depend not only on the parameters of the VNA in the frequency domain, but also on the properties and configuration of the device under test (DUT) in the time domain.

Measurement of delay (or distance) primarily depends on two factors:

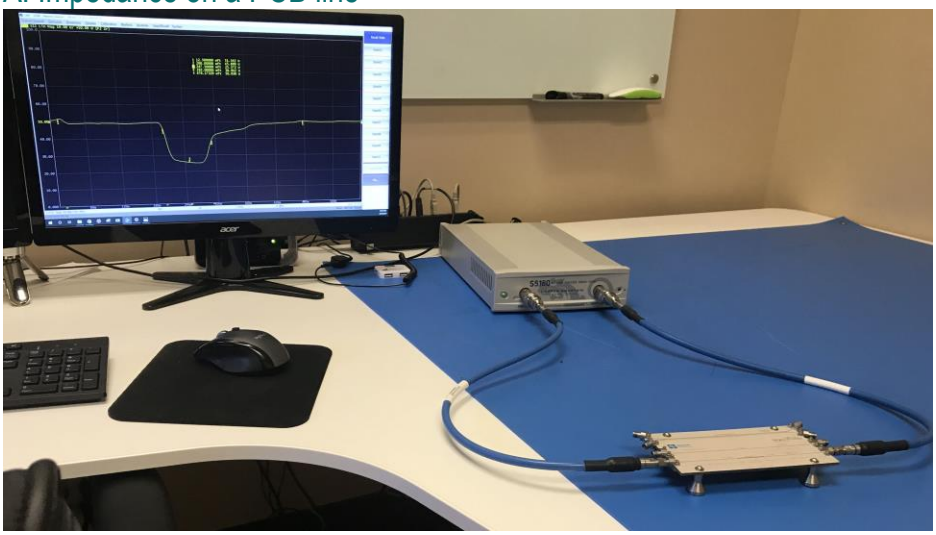
First, the frequency span or the maximum frequency of the VNA determines the resolution in time domain (inversely proportional as mentioned above in the 'Calculator' section). Based on the transformation setting, the maximum error can be equal to half the resolution:

$$\Delta\tau_{max} = \frac{1}{2f_{max}} \text{ (band-pass mode)} \quad \Delta\tau_{max} = \frac{1}{4f_{max}} \text{ (low-pass mode)}$$

Secondly, when the delay is recalculated into distance considering the value of the effective permittivity of the medium. The error in known permittivity increases the error in calculating the distance.

COMMON APPLICATIONS

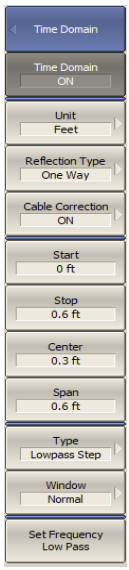
A: Impedance on a PCB line



Setup

S5180 VNA (2-port, 100 kHz to 18 GHz), two N-type to 3.5 mm adapters, two 2.92 mm coaxial cables and a sample board with a 25 Ohm Beatty line.

Steps



1) Set the stimulus settings: frequency span, points, and linear sweep type.

2) Click 'Set Frequency Low Pass' to create a harmonic grid (*Analysis* > *Time Domain* > *Set Frequency Low Pass*).

3) Perform full 2-port calibration at the measurement plane (*Calibration* > *Calibrate*).

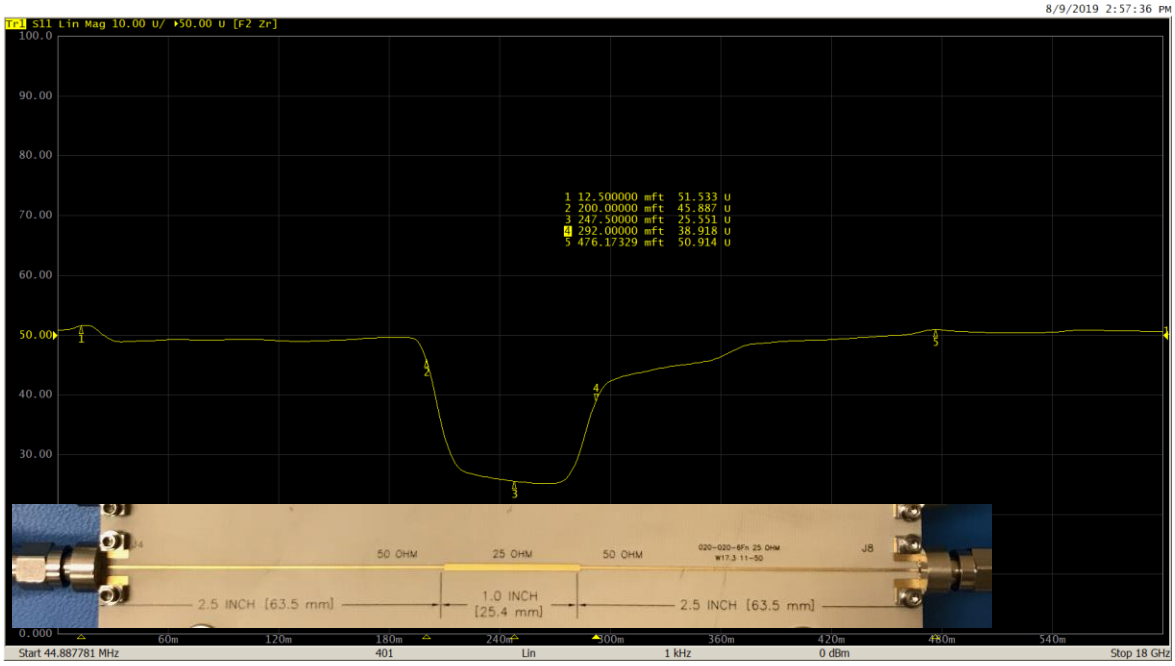
4) Adjust time domain settings (*Analysis* > *Time Domain*): unit, reflection type – one way, velocity factor and loss, start and stop value, transformation type – Lowpass step, Window – Normal.

5) Enable time domain mode (*Analysis* > *Time Domain* > *ON*).

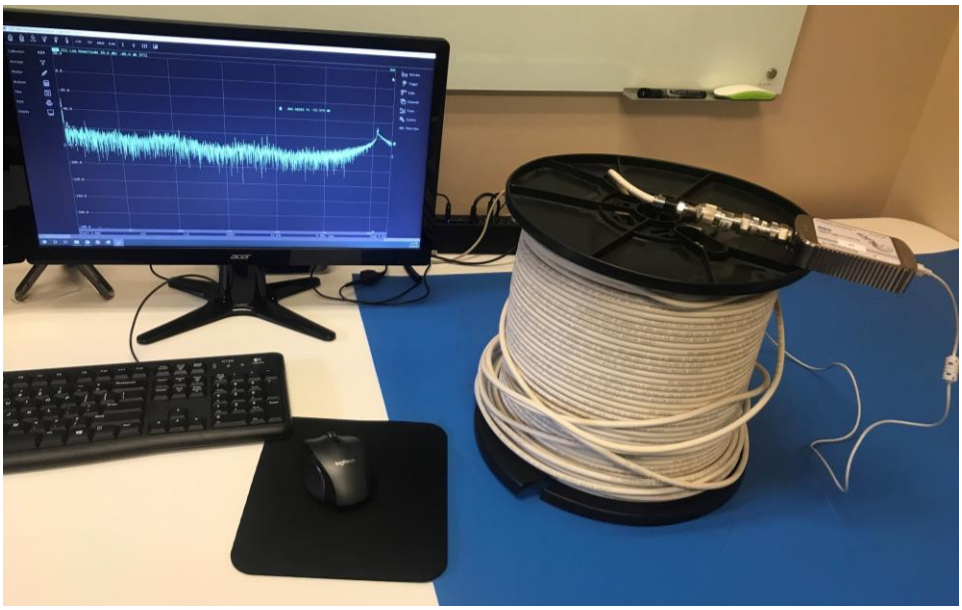
6) Adjust the display settings to measure impedance (y-axis) vs. distance (x-axis):

   a) Set trace to 'S11 linear magnitude'.
   b) Enable impedance measurement (*Analysis* > *Conversion* > *Function – Z:Reflection* > *ON*).

Measurement



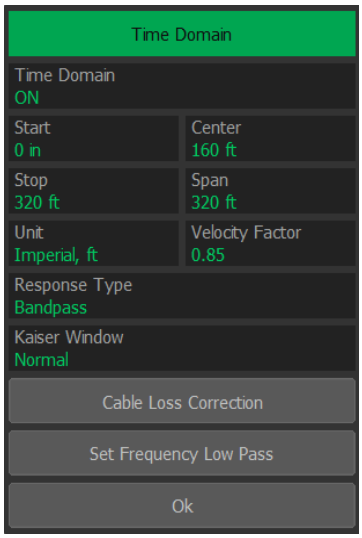
B: DTF on a long cable



Setup

R60 VNA (1-port, 1 MHz to 6 GHz), one N-type 50 Ohm barrel, one N-type 50 Ohm to 75 Ohm adapter, one N-type to F-type adapter, one 300-foot-long CATV cable under test.

Steps



1) Set stimulus settings: frequency span, points, and linear sweep type.

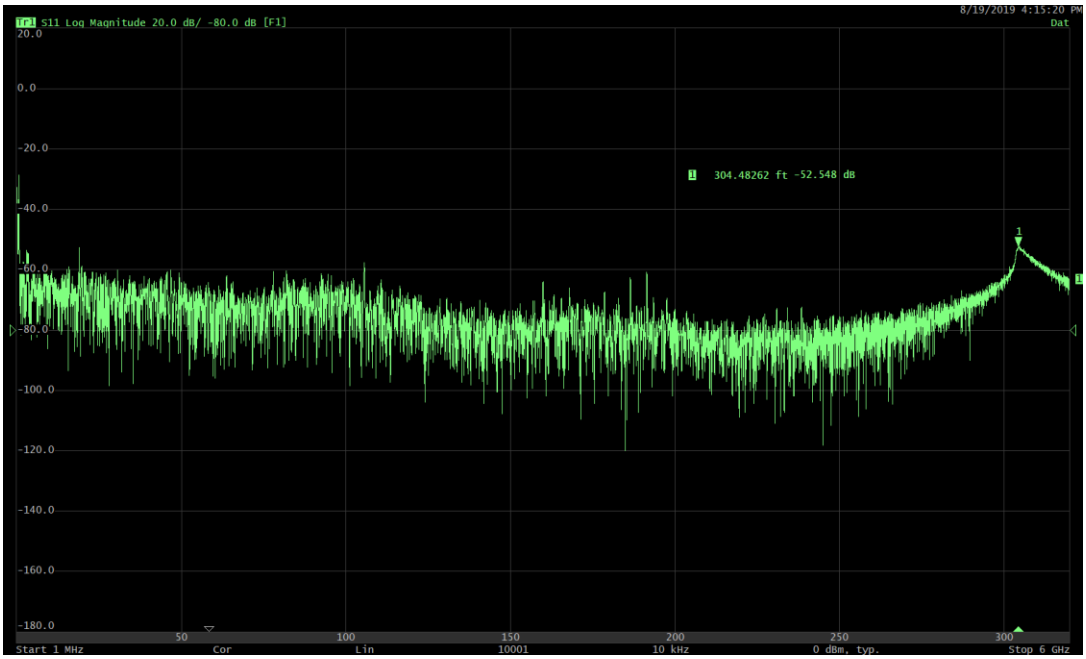
2) Perform full 1-port calibration at the end of the measurement plane (*Calibration* > *Calibrate*).

3) Adjust time domain settings (*Analysis* > *Time Domain*): unit, reflection type – one way, velocity factor and loss, start and stop value, response type – Bandpass, Window – Normal.

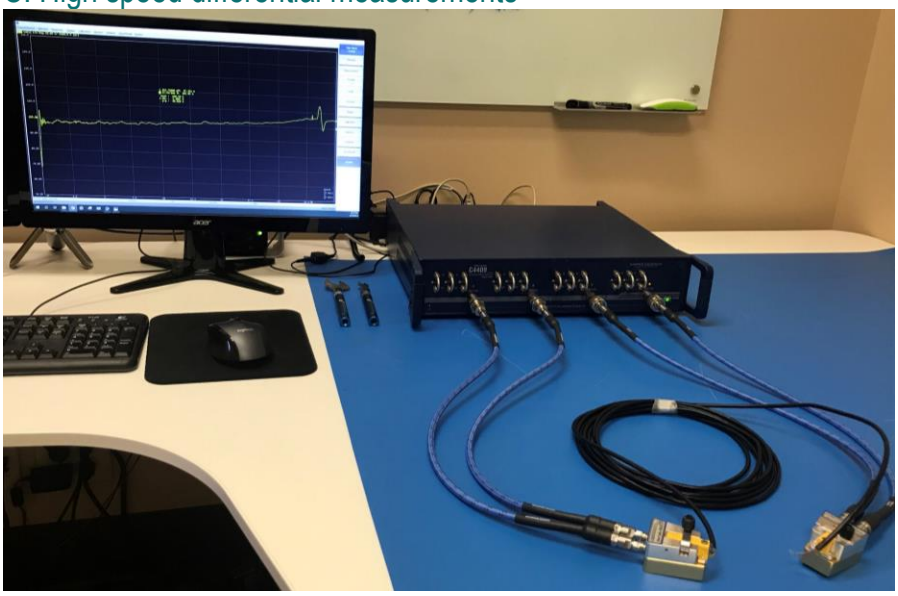
4) Enable time domain mode (*Analysis* > *Time Domain* > *ON*).

5) Adjust the display settings to measure return loss (y-axis) vs distance (x-axis) (Trace > Format – Log Magnitude)

Measurement



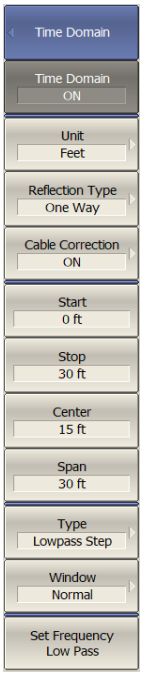
C: High speed differential measurements



Setup

C4409 VNA (4-port, 100 kHz to 9 GHz), four N-type to 3.5 mm adapters, four 2.92 mm coaxial cables, two coaxial to raw cable fixtures and a 100 Ohm differential high speed LVDS cable under test.

Steps



1) Set stimulus settings: frequency span, points, and linear sweep type.

2) Click 'Set Frequency Low Pass' to create a harmonic grid (*Analysis* > *Time Domain* > *Set Frequency Low Pass*).

3) Perform full 4-port calibration at the end of the coaxial cables (*Calibration* > *Calibrate*).

4) De-embed the fixtures using the touchstone files provided by the manufacturer (*Analysis* > *Fixture Simulator* > *De-Embedding s4p*).

5) Enable balanced mode to measure the differential parameter Sdd11 (Analysis > Fixture Simulator - ON> BalUn - ON)

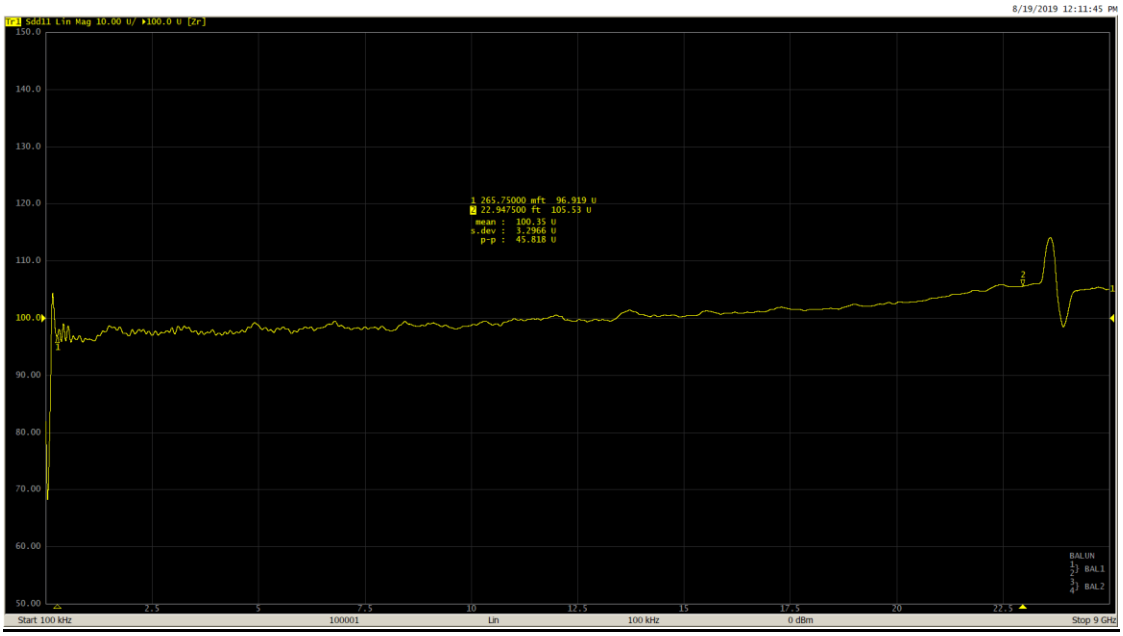
6) Adjust the time domain settings (*Analysis* > *Time Domain*): unit, reflection type – one way, velocity factor and loss, start and stop value, transformation type – Lowpass step, Window – Normal.

7) Enable time domain mode (*Analysis* > *Time Domain* > *ON*).

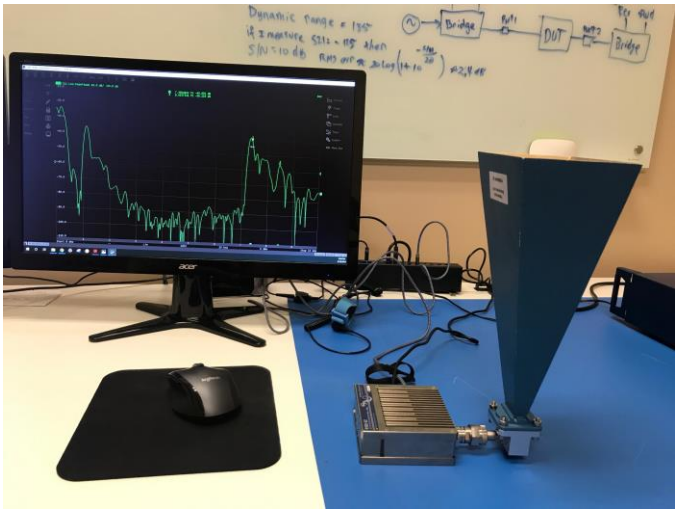
8) Adjust the display settings to measure impedance (y-axis) vs distance (x-axis):

   a) Set trace to 'Sdd11 linear magnitude'.
   b) Enable impedance measurement (*Analysis* > *Conversion* > *Function – Z:Refletion* > *ON*).

<u>Measurement</u>



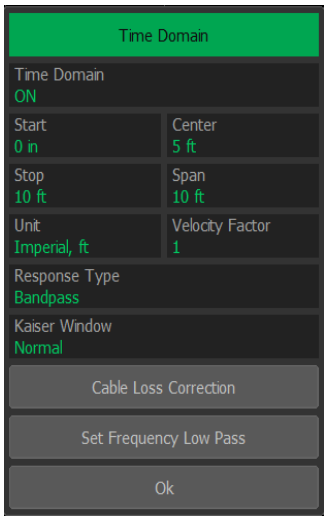
D: X-band horn antenna



Setup

R180 VNA (1-port, 1 MHz to 18 GHz) and X-band antenna

Steps



1) Set stimulus settings: frequency span, points and linear sweep type.

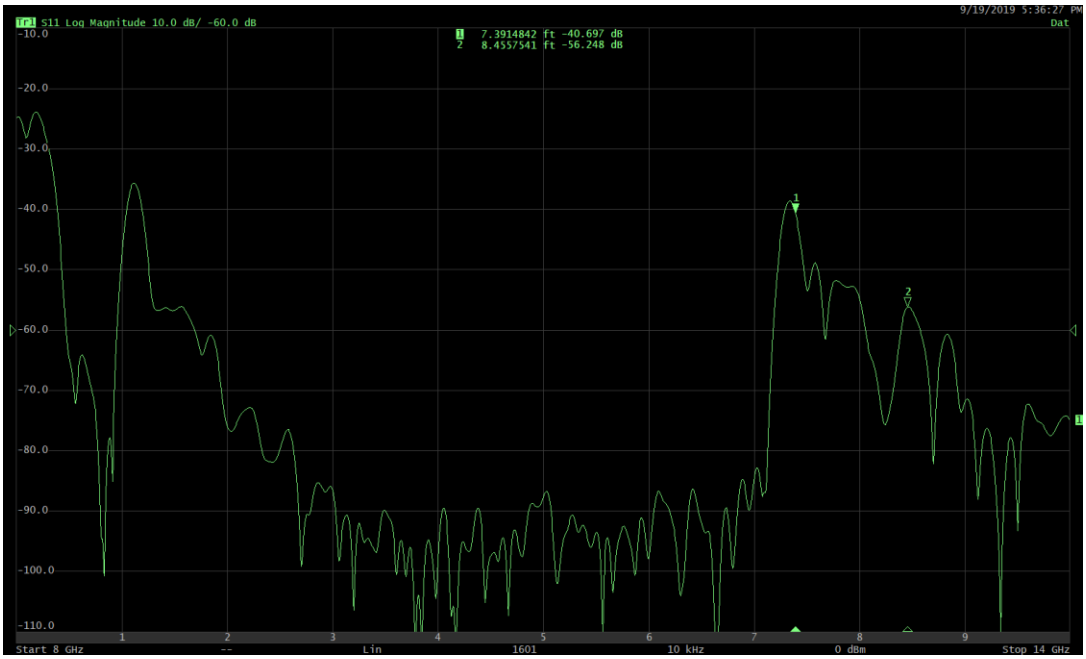
2) Perform full 1-port calibration at the end of the measurement plane (*Calibration* > *Calibrate*).

3) Adjust time domain settings (*Analysis* > *Time Domain*): unit, reflection type – one way, velocity factor and loss, start and stop value, response type – Bandpass, Window – Normal.

4) Enable time domain mode (*Analysis* > *Time Domain* > *ON*).

5) Adjust the display settings to measure return loss (y-axis) vs distance (x-axis) (Trace > Format – Log Magnitude)

Measurement



CONCLUSION

As a VNA measures both the magnitude and the phase of the DUT in frequency domain, we have seen that using the built-in inverse Fourier transformation algorithm measurements could be viewed in the time domain mode as well. We have seen how different settings can impact the time domain transformation, and the various applications that could be performed using this feature.

If you need further information on this application note or any assistance with your application, please contact: support@coppermountaintech.com.

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