Anritsu

Time Domain for Vector Network Analyzers

Lightning™ VNA

Introduction

Vector Network Analyzers (VNAs) are very flexible measuring instruments – the microwave engineer's most powerful tool. Their basic capability is to measure the S-parameters of an RF or microwave device and display the result in the frequency domain. This provides valuable data for the design engineer to develop a design and for the production engineer to substantiate the performance of the device or system. The Time Domain option is available to enhance the flexibility of the VNA by presenting data that provides insight into the time (or distance) performance of the device – valuable information for both the design and production engineer. Figure 1 shows both the time and frequency response of a microstrip circuit. The benefit of the Time Domain response is apparent.
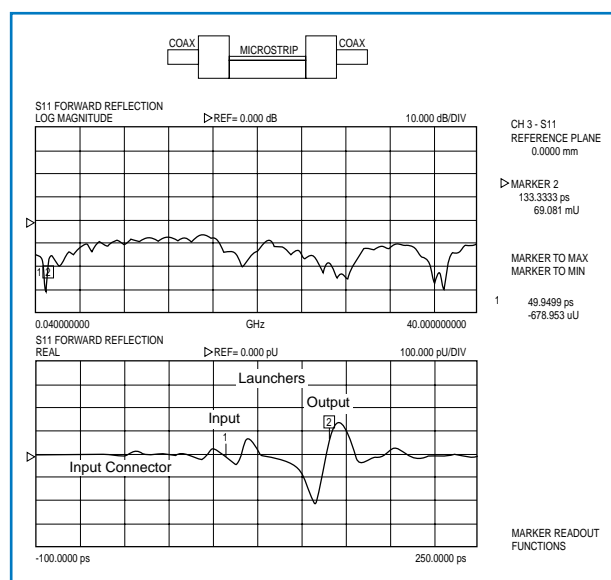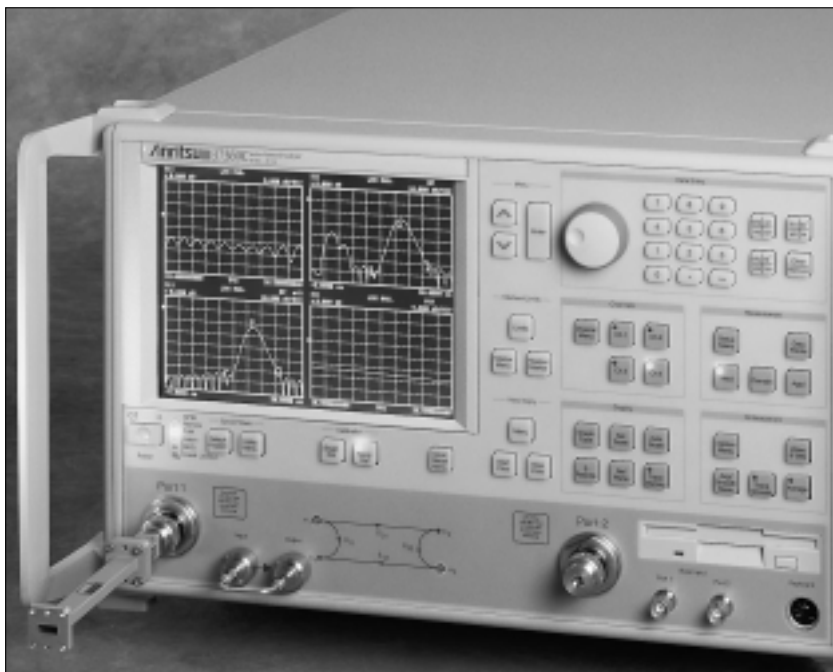
Figure 1. The Time and Frequency Response of a Microstrip Circuit

Time Domain Fundamentals

The Fourier transform has been used in many technologies and in the area of microwave measurements, it provides a method for transforming frequency domain data, the VNA's basic capability to the time domain. Digital Signal Processing, that is fundamental to the modern VNA by computing error correction terms, also permits convenient implementation of the Fast Fourier Transform (FFT). Actually a type of FFT known as the Chirp Z Transform is used. This permits the user to "zoom in" on a specific time (distance) range of interest for the data display. This application note will address properties of the transform process and show how the various processing options can be used to obtain optimum results for a given application. It will not address the algorithmic details of the FFT.

A convenient place to start is to consider the transform of frequency domain data obtained from the measurement of a short at the end of an airline–see Figure 2. It is apparent that the time domain response is informative; but it is far from the ideal time domain response that is superimposed. This figure illustrates two of the fundamental properties (limitations) associated with the FFT–resolution and alias free range. These are due to the fact that the FFT is operating on a finite set of data rather than the theoretical infinite set.

The principal property of time domain processing for most microwave applications is resolution–that relates to the ability to locate a specific signal in the presence of other signals. In practice the basic limitation is inversely related to data collection bandwidth in the frequency domain. A rule of thumb: resolution is on the order of 150 mm/Frequency Span (GHz)–that is a 40 GHz frequency span will provide resolution of about 4mm. Figure 3 illustrates the importance of a wide frequency sweep if the application calls for identifying closely spaced reflections. Resolution is also influenced by the processing method and window selection that are described below. Another important factor is the relative amplitude of the signals being processed. A large signal can swamp a smaller signal–obviously the greater the time (distance) separation between the two the better the system will perform.

A second property of the transform process is the Alias Free Range. The transform is a circular function and repeats itself outside of its inherent range that is 1/Step Size. This is not usually a factor in circuit measurements; but does become a factor in fault location which is an important application for the Time Domain Option. For example, with a 20 GHz, 401 point frequency collection the Alias Free Range is:

1/50 MHz = 20 nanoseconds

This is large for most circuit work and the range is usually greatly reduced for display. However, if the user wanted to locate a fault in a 100 meter cable, the range is inadequate. For such applications the step size must be reduced either by decreasing the frequency span or increasing the number of points.

Processing Options:

The Time Domain option offers a number of processing options to the user. It is important that the user be aware of the feature set available as selection can have a significant effect on the end result. These "tools" include:

- Processing Method – Lowpass, Bandpass or Phasor Impulse
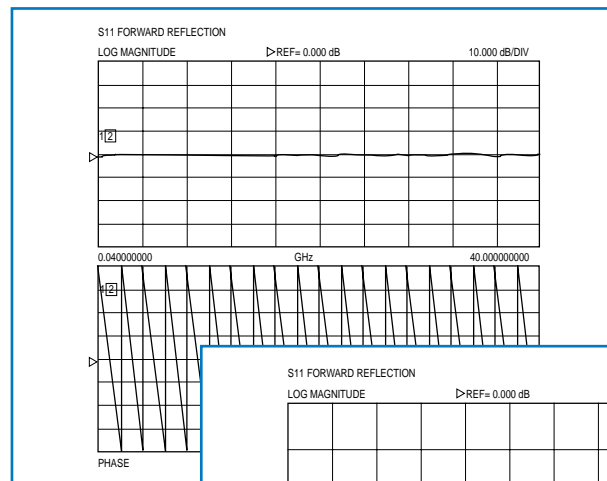
- Windows

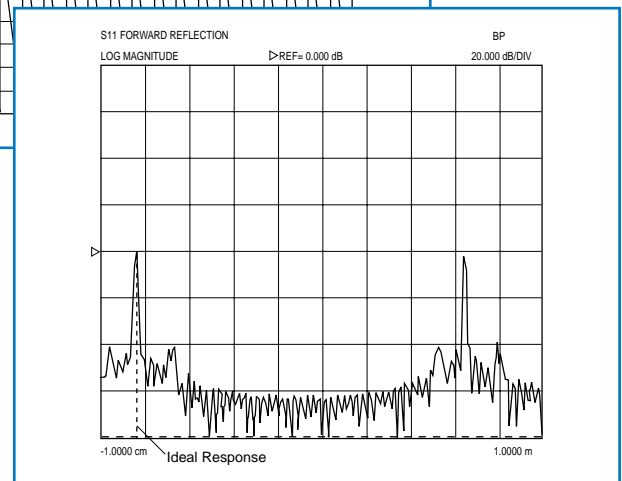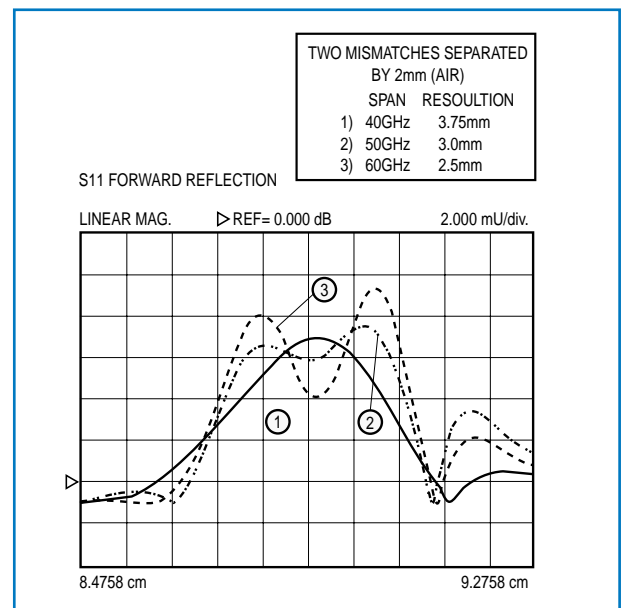- Gating – Frequency Gated by Time Display

Figure 2a

Figure 2b

Figure 3. A Wide Frequency Sweep if the application calls for identifying closely spaced reflections

Lowpass - This is the most powerful processing technique. It does require a special frequency plan: a harmonically related set of frequencies that starts at the lowest frequency possible. A DC term is extrapolated that provides a phase reference, so that the true nature of a discontinuity can be seen. Lowpass offers two presentations: Step or Impulse response. (The Step response is the integral of the Impulse response). The Step response permits the direct display of impedance versus time or distance similar to that obtained with a Time Domain Reflectometer. The user can also obtain insight into the nature of a discontinuity: inductive, capacitive or resistive. Figure 4 shows ideal responses associated with various types of discontinuities. The default display graph type is real and shows impedance information (A scale of 20 mU per division is about 2 ohms per division). There is no imaginary component in the time display for Lowpass processing. The user can also choose Log Mag or a linear display format (standard for Bandpass described below). Lowpass processing also offers the highest resolution for a given bandwidth. If the instrumentation, transmission line and DUT permit Lowpass processing, it should be used.
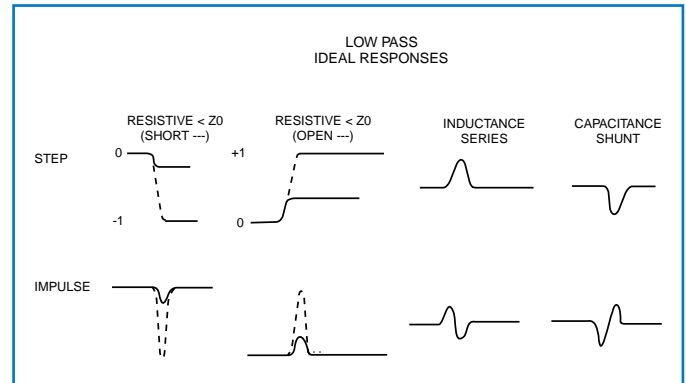

Figure 4. Ideal Responses Associated with Various Types of Discontinuities
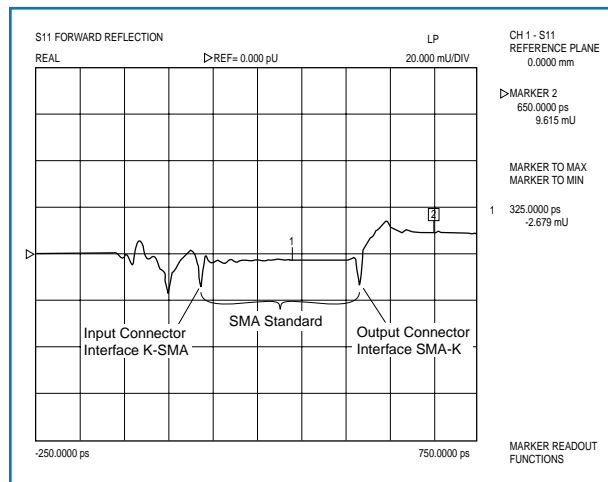

Figure 5. A Practical Application of Lowpass Time Domaining Processing

Figure 5 shows a practical application of Lowpass Time Domain processing. An SMA line standard was constructed using solid teflon and precision connector interfaces, the response clearly shows the quality of the SMA "standard" that was used to evaluate SMA calibration performance. The standard line impedance is 49.73 ohms that provides greater than 50 dB return loss.

Bandpass – Many situations such as waveguide or band limited DUTs preclude using a broadband harmonically related frequency plan. For these cases Bandpass processing can be used. In this situation there is no phase reference, so vector information is lost, but useful magnitude information is still available. It can be displayed in either log magnitude or linear form. Figure 6 shows the Bandpass response of the SMA "standard" that was used in Figure 5. This type of processing is common in fault location that can be used to test transmission lines. Figure 7 shows an example of this application: measuring a 2m cable with imperfections.
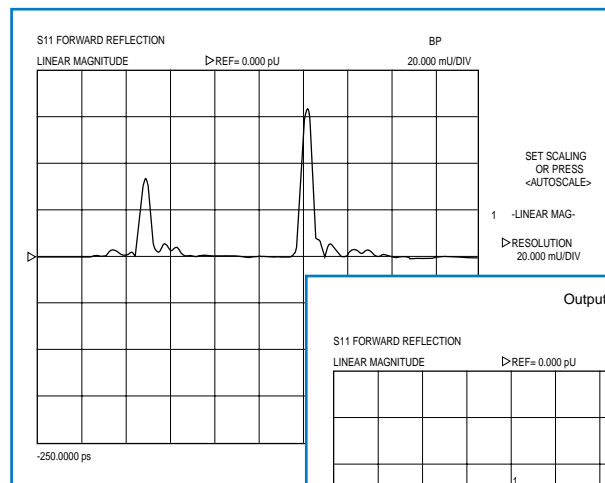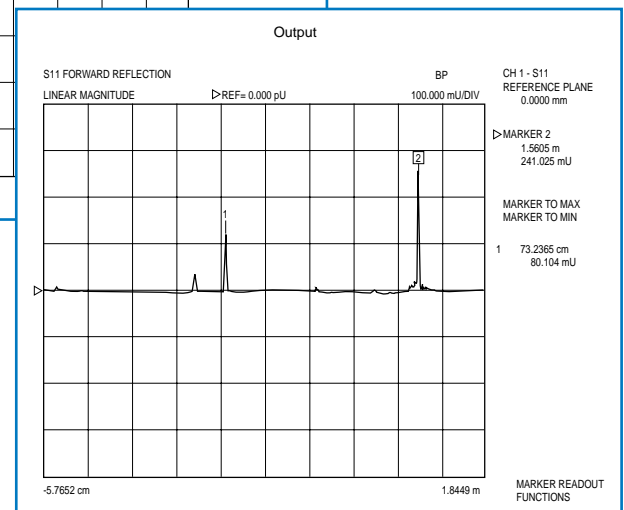

Figure 6. The Bandpass response of the SMA "Standard"

Figure 7. Measuring a 2m Cable with Imperfections

Phasor Impulse – This technique that is exclusive to Anritsu VNAs enables the user to extract impedance information for a specific discontinuity from a Bandpass display. The discontinuity of interest must be positioned in the center of the screen and it should fill about 50% of the time range being displayed. Then when the Phasor Impulse processing is applied the resulting display, usually Real, Imaginary, or Linear Polar, provides the desired impedance information. Figure 8 shows the shunt capacitance associated with a waveguide iris.

Figure 9 is a summary of the processing types. It should be apparent that if Lowpass processing is possible it should be used as it offers the highest performance and most versatile set of displays.
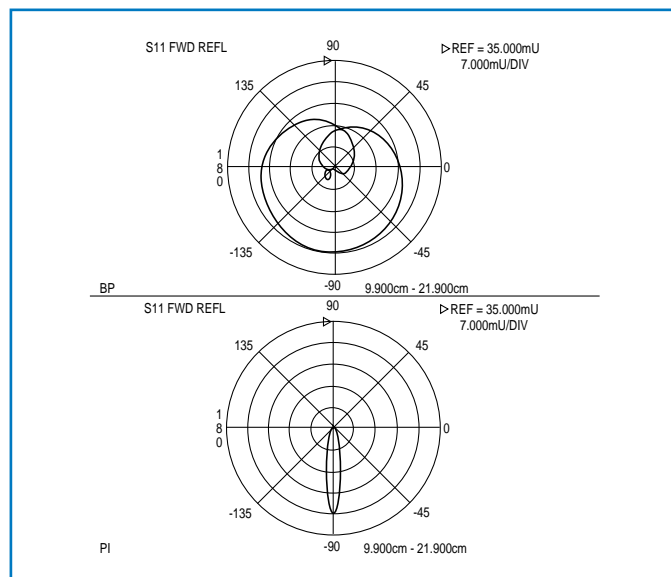

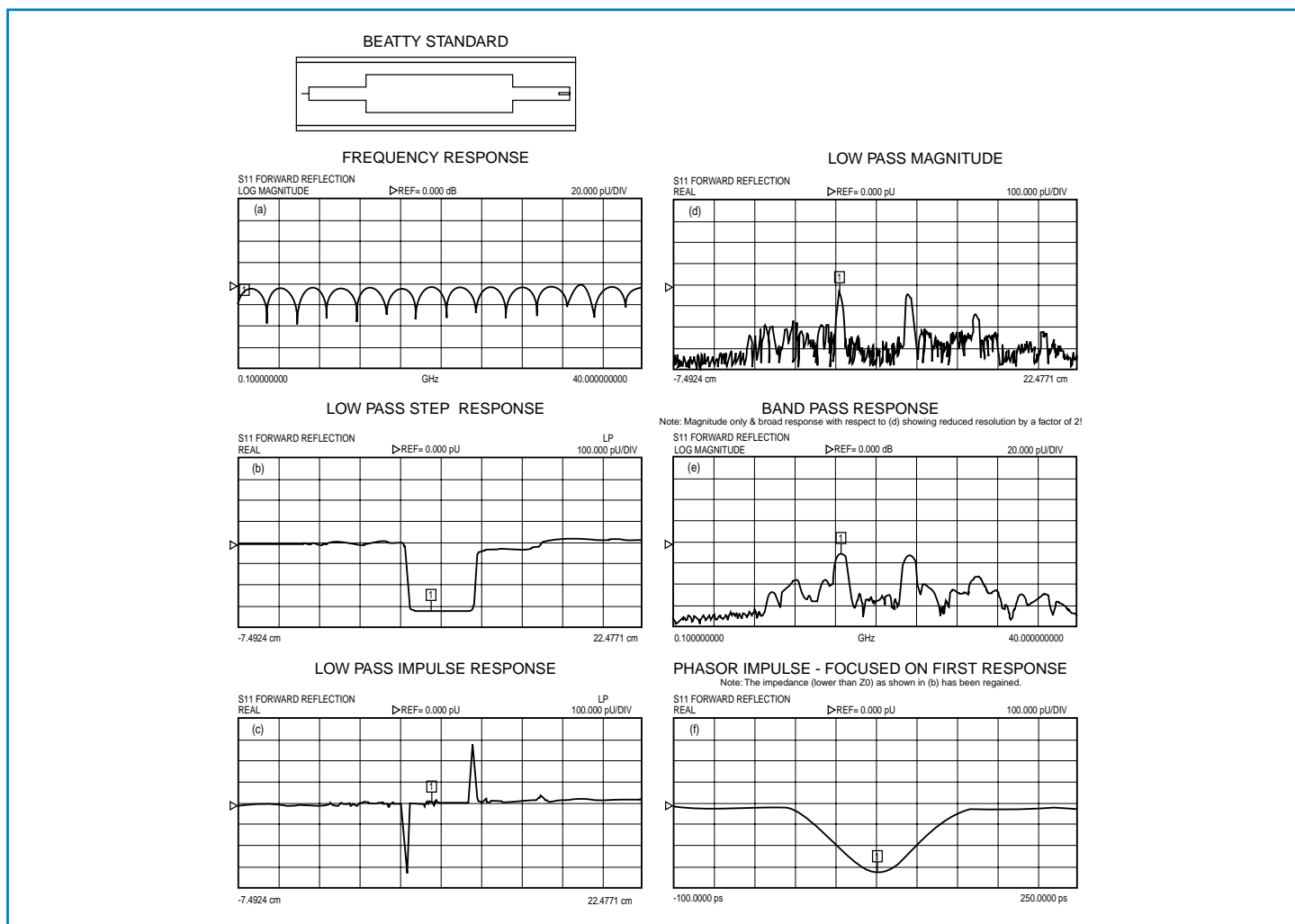*Figure 8. Normal Bandpass Display and the Phasor Impulse Display of Waveguide*

Figure 9. Summary of Processing Types

Windows

Windows are used to "condition" data prior to transformation. They are used to get around the Fourier transforms basic, but impractical – to + form and they are used to mitigate edge effects associated with a finite data set. The application of what is called a "window" function to the frequency domain data will accomplish this. The window is a curve derived from a mathematical function (many are available–see reference 4) that tapers off from unity gain at the center of the frequency domain data to a low value at the ends. Figure 10a and 10b show the effect of applying the widely used two term Hamming window to the data array obtained by measuring the short circuit shown earlier. The resulting time domain displays are shown in 11a and 11b. This is not without a price, since the window has the effect of widening the main lobe, thus decreasing the effective resolution. For this reason it is good to have a range of different window types available so that a compromise, appropriate for the application, between resolution and sidelobe level can be reached. The Anritsu VNAs offer the window choices described in Table 1. Resolution has been normalized to the Default Nominal window that is adequate for most applications.
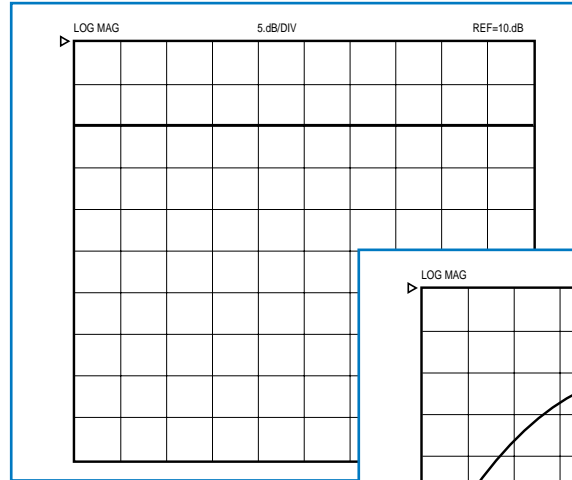

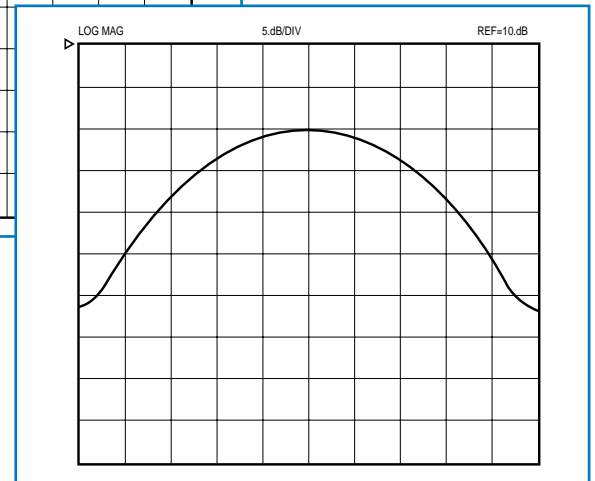Figure 10a. Frequency Domain Data Before Application of Hamming Window

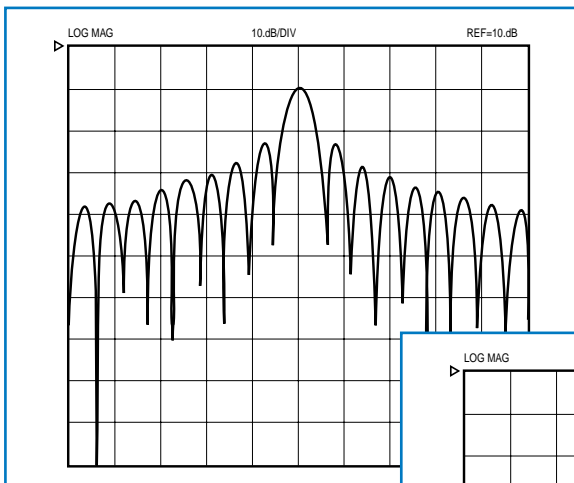Figure 10b. Frequency Domain Data After Application of Hamming Window

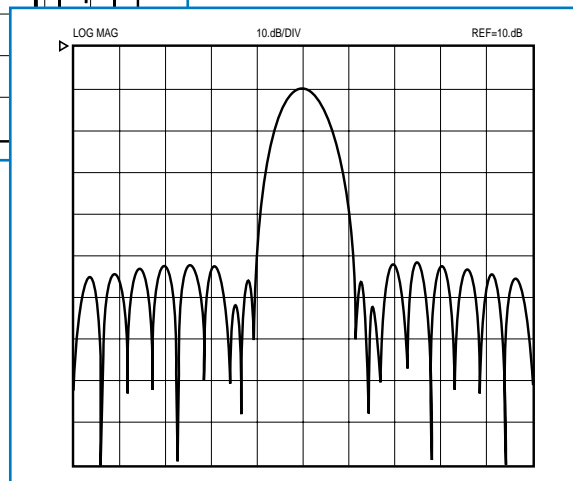Figure 11a. Time Domain Data Before Application of Hamming Window

Figure 11b. Time Domain Data After Application of Hamming Window

Gating – Frequency Gated by Time

The Gate is essentially a filter in the time domain. It is set by the operator while observing the time domain response to select a given discontinuity or in some cases to select those responses that can be attributed to given DUT, such as a cable that has principal reflections at both ends. It can also be used to Gate out a specific discontinuity, such as a test fixture, thus observing the performance of a microwave circuit with an imperfection removed. This permits observing the selected range without the influence of unwanted elements, such as connectors or in the case of transmission measurements: multipath signals. The Gating process also involves a "conditioning" Gate Shape. This is similar, but not identical to the Window function. In looking at previous time domain displays, it is apparent that there are ripples associated with a specific reflection, that extend over the time range. All of which are necessary to obtain a good representation of that reflection in the frequency domain. The gating process can eliminate some of this necessary data that can introduce errors or ripple in the frequency domain response. As in Windowing, the solution is to provide a selection of Gate functions so the user can obtain the best tradeoff of resolution versus ripple.

Window Type	Main Lobe Width Lowpass	Main Lobe Width Bandpass	Sidelobe Level (dB)
Rectangular	0.5/BW	1/BW	−13
Nominal	1/BW	2/BW	−42
Low sidelobe	1.5/BW	3/BW	−70
Min sidelobe	2/BW	4/BW	−90

Table 1

Figure 12 shows the application of a Gate and the Frequency Gated by Time display of the initial discontinuity of the Beatty standard used in Figure 9 above. This figure also illustrates the processing sequence that can be observed when a four channel display is available. Each channel is set to S11 and each is set up with a different process, the final in the lower right showing the frequency gated by time response of an impedance step that is reasonably flat with frequency as expected.

User Interface

The user interface for Time Domain is designed to give the user a simple but flexible way of selecting processing options and controlling the display. All of the controls required are grouped together in a few menus. The menus also include full screen HELP displays for each major area. During the calibration process the recommended harmonic frequency plan can be selected and it is automatically established. The instrument, which offers a four channel display, permits the user to display data with up to four different types of processing which permits viewing the effects of the processing steps (as shown in Figure 12) or to observe the effects of a change in several different ways. The user can select whether the annotation of each display and its associated markers is given in units of time or distance.
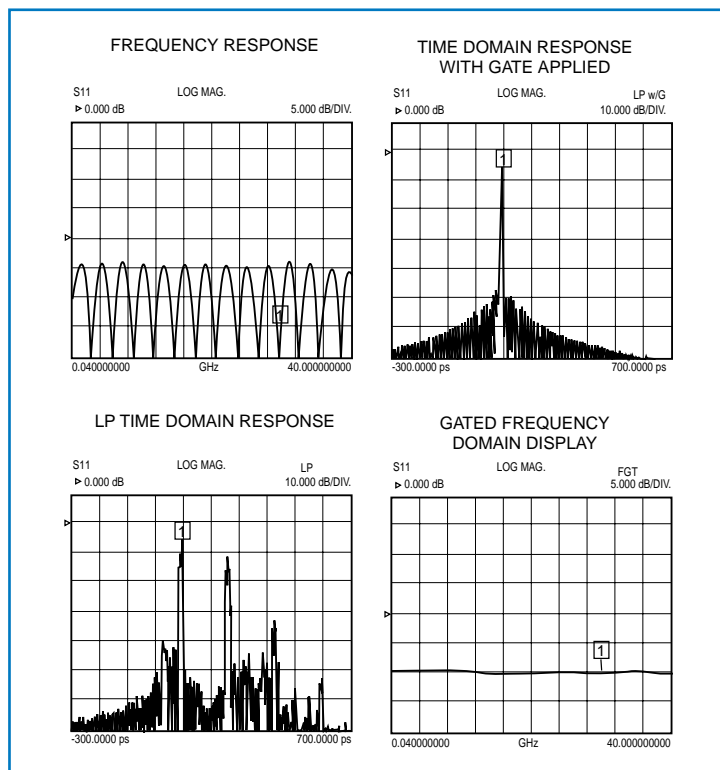

Figure 12. The application of a Gate and the Frequency Gated by Time display of the initial discontinuity of the Beatty standard.

What Time Domain Can Do For You

Time Domain is most useful when analyzing broadband low loss devices. This includes transmission lines, connectors, test fixtures and similar components. Narrowband devices such as filters, isolators or matching networks are not good candidates for Time Domain measurements. A few "Helpful Hints":

A harmonic frequency set is most desirable as this permits low pass processing. In any application use the widest frequency range possible.

The VNA should be calibrated, but the calibration doesn't have to be perfect. As long as the cable environment is intact, "old" calibrations will provide good results. Figure 13 shows the measurement of an offset termination measured with a precision calibration, a typical OSLT calibration using a broadband termination, and a frequency response calibration.

When interpreting the return loss value of a Time Domain response it must be noted that the response is the average of the return loss over the entire frequency range.

When using frequency gated by time it is important to center the gate around the discontinuity, or circuit being analyzed. In general the gate should be as wide as possible, but not too close to responses that the user wants to eliminate.

The selection of Window and Gate shapes can have a significant effect on the result. For most applications the default values will provide good results. For some applications the user can establish a set of Window and Gate shapes that optimize a result. In these cases if correlation with other measurements becomes an issue it's important that the same Window and Gate shapes are used.

Assurance Airlines

Time Domain work is greatly enhanced when the reflection(s) to be studied are well separated from other reflections. This is readily accomplished if a high quality transmission line can be included in the system to be measured. In a coaxial system this would be an airline with connectors that interfaced to the other components with minimum reflections. This performance can be realized by airlines with a beaded interface at one end, and a floating center interface at the other end. The bead insures an accurate pin depth at the precision interface, and also supports the center conductor so the airline can be easily installed. Such airlines are available with GPC-7, N, 3.5 mm, and K Connectors. They were used in two of the example applications.

The following examples show a number of practical applications for Time Domain processing:

Designing a Test Fixture –
In test fixture design it's often desirable to have an input coaxial connector, and a launch to the microstrip medium being used for circuit design. This launch should be designed for minimum SWR so that it will be transparent when the device design is being evaluated. This can be accomplished by starting with a short length of microstrip line (several centimeters is a good choice) and connecting it to the initial launcher design, leaving the other end open. Figure 14 shows a coaxial to Duroid microstrip design. The reflection from the launch is clearly distinguished from the open end. The designer can make modifications to the launch design and easily see their effect until a satisfactory launch interface is obtained.

Measurement of VNA Directivity and Port Match –
The accuracy of a VNA reflection measurement is primarily related to the effective directivity and port match after calibration. These parameters are usually specified in data sheets, but are dependent upon calibration standards and user technique. In some cases it would be nice to know the value of these parameters. This information can be readily obtained if an Assurance Airline is available. It is installed at the calibrated test port and terminated with a short circuit. Figure 15 shows by diagram what is happening, the port match, directivity, and the short reflection are clearly separated in time and can be distinguished and evaluated quantitatively. The results show the result of an OSLT calibration using a broadband termination.
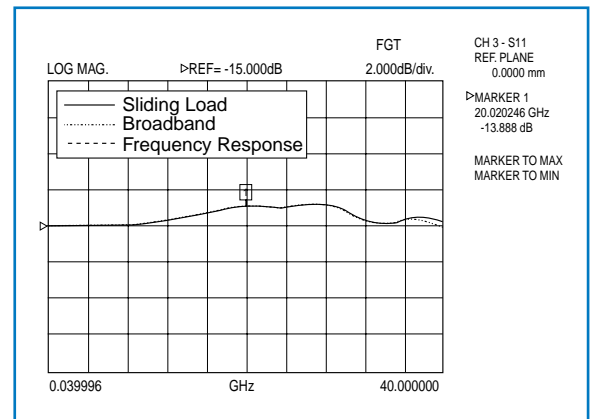

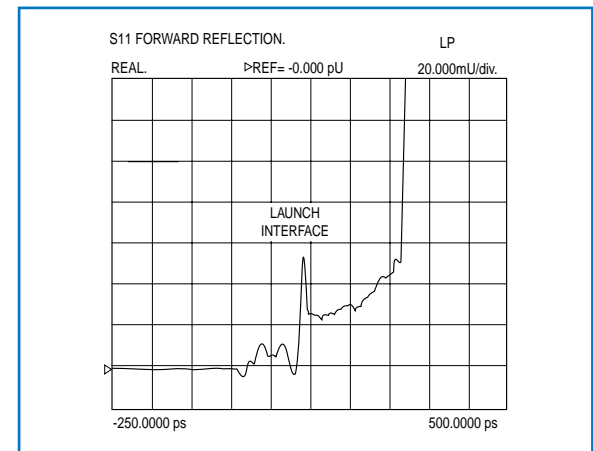Figure 13. Measurement of an Offset Termination measured with a precision calibration

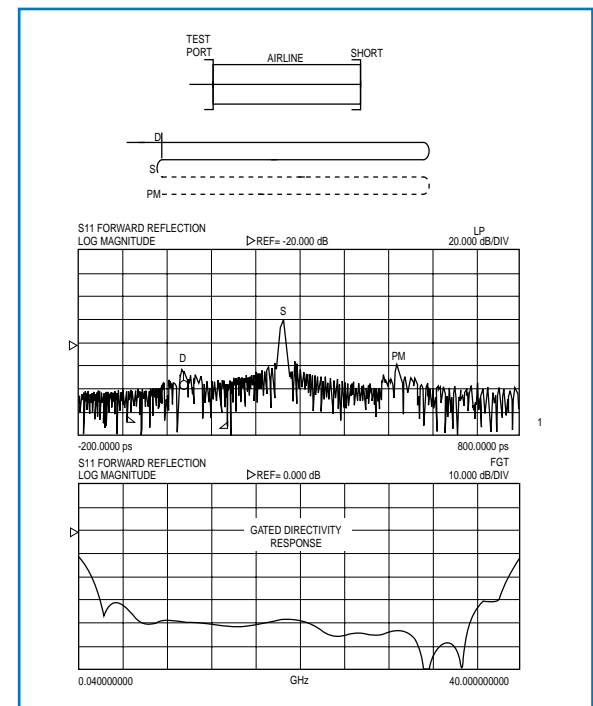Figure 14. Coaxial to Duroid Microstrip Design

Figure 15. Port Match, Directivity, and Short Reflection clearly separated in time.

Rise Time Measurements using Time Domain Transmission

The advent of data transfer rates in the tens of GHz region has precipitated the need to measure the rise time and propagation delay of wide band devices such as coaxial cables, switches, and amplifiers used in optoelectronic systems. The use of sampling oscilloscopes in conjunction with fast rise pulse generators is a common technique for measuring rise time and delay. However, as VNA bandwidths have surpassed those of the scopes, the VNA provides an alternative means of performing the rise time and propagation delay measurements of these high speed devices.

These measurements require the use of Time Domain Transmission, i.e. S21 Step response. The VNA performs these measurements with rise times as fast as 9 picoseconds (110 GHz system). The Processing options – Lowpass, Bandpass and the Gating feature discussed earlier, apply to S21 Time Domain response as well.

In addition, the error correction techniques available on the VNA allow more accurate measurements of rise time, which may be obscured by the adapters and cables which are usually uncorrected in the oscilloscope method.

The Rise Time measurement of a 40 Gb/s driver amplifier using the ME7808A (110 GHz VNA) is discussed in this section. A measurement of the rise time of the VNA transmission response is required in order to make the amplifier measurement. In this case, a 12-term calibration is performed and with the thruline in place, the S21 time step response is measured as shown in Figure 16. The rise time, i.e. the time between the 10% and the 90% magnitude points is measured to be approximately 9 ps.

The 40 Gb/s driver amplifier is then measured (Figure 17). The S21 Time Domain response in this case is the composite measurement of the VNA rise time and the Amplifier rise time. The 180˚ phase shift in the amplifier S21 response is displayed as an inverted step in Time Domain mode. The composite rise time measured is 12 ps.

Rise time of the amplifier can then be calculated by using the root sum squares theorem:

$$T_R^2 \text{ (DUT)} = T_R^2 \text{ (total)} - T_R^2 \text{ (input step)}$$

$$\text{Or, } T_R \text{ (amplifier)} = \sqrt{[(12)^2 - (9)^2]}$$
$$= 8 \text{ ps}$$

Similarly, the propagation delay through the amplifier can be measured from the 50% point of the step response.

$$\text{Time Delay } T_d \text{ (amplifier)} = 30 \text{ ps}$$

Figure 16. Corrected Step response of the 110 GHz VNA
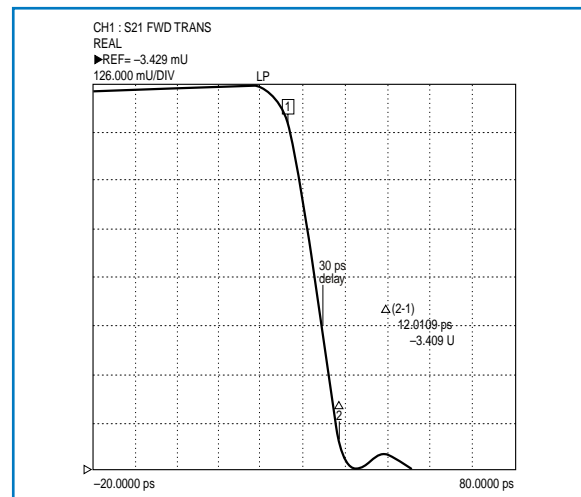
Figure 17. Inverted rise time and propagation delay response of the amplifier

References

1. M. Hines and H. Stineheifer, "Time Domain Oscillograph Microwave Network Analysis Using Frequency Domain Data IEEE Transactions on Microwave Theory and Techniques", V MTT-22, No. 3, Mar. 1974.

2. L.R. Rabiner, "Chirp z-Transform Algorithm Program", Programs for Digital Signal Processing, Ed. by the Digital Sign Processing Committee, IEEE Acoustics, Search and Sign Processing Society, New York, IEEE Press, 1979.

3. L.R. Rabiner and B. Gold, "Theory and Application of Digital Signal Processing", Prentice-Hall, Englewood Cliffs, NJ, 1975.

4. Fredric J. Harris, "On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform", in Proceedings of the IEEE Vol. 66, No. 1, pp 51-83, Jan. 1978.

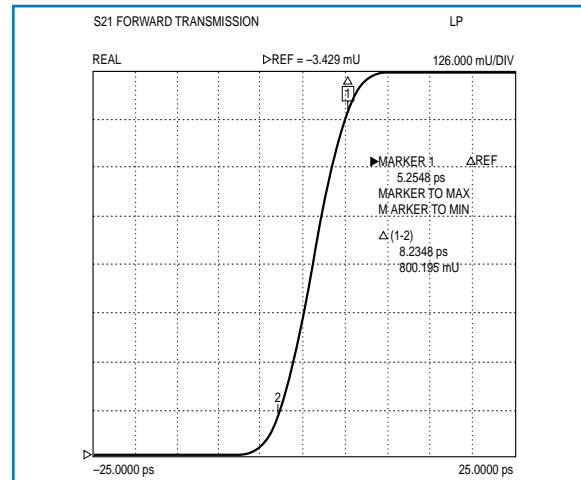5. N. Marcuvitz, Waveguide Handbook, New York, McGraw-Hill, 1951.
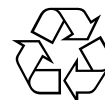
/Anritsu

Discover What's Possible®