# SCALAR NETWORK ANALYSIS: AN ATTRACTIVE AND COST-EFFECTIVE TECHNIQUE FOR TESTING MICROWAVE COMPONENTS

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**Measurement**
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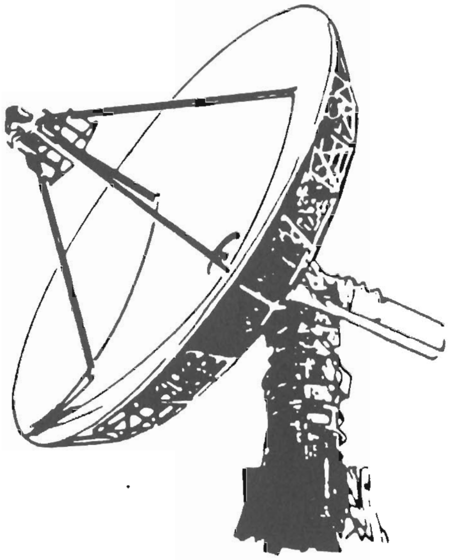

# Scalar Network Analysis: an Attractive and Cost-Effective Technique for Testing Microwave Components

## ABSTRACT

Scalar network characterization is an economic alternative to vector network analysis; in particular, in a productive environment where ease-of-use, throughput and low cost are key considerations.

However, scalar measurements are not restricted to frequency response measurements on linear networks. Scalar network analyzers are very powerful analysis tools to characterize amplifiers, mixers, modulators, and other components as a function of signal level or control parameter, as well as for cable testing in frequency- and distance-domains.

This presentation describes the fundamental measurement concepts and discusses some specific examples.

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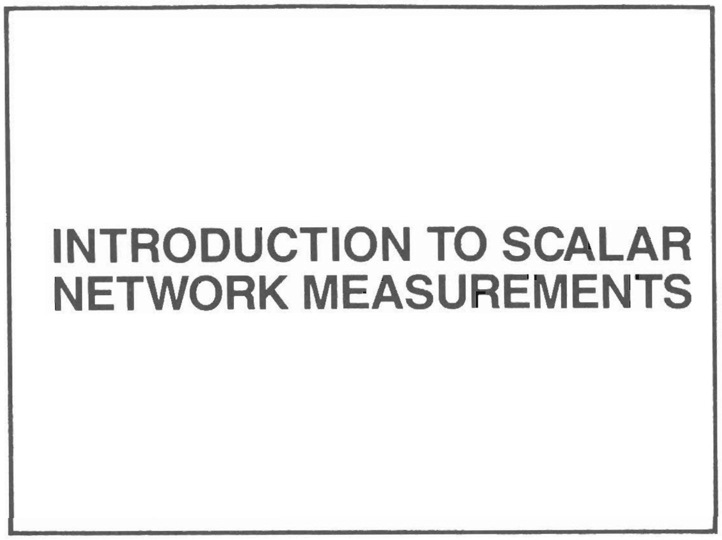
INTRODUCTION TO SCALAR NETWORK MEASUREMENTS

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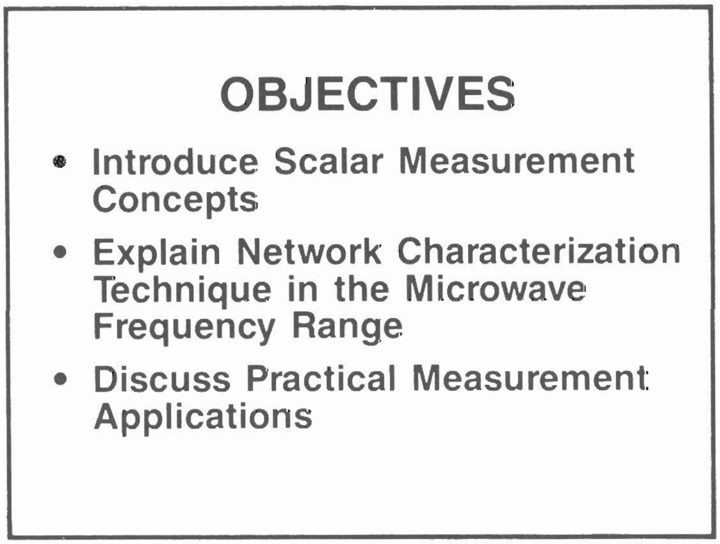
## INTRODUCTION TO SCALAR NETWORK MEASUREMENTS

Introduction: Even though scalar microwave measurements have been made ever since high frequencies were discovered, they were not really addressed, as such, but rather called power measurements or VSWR measurements, etc. It was not until modern network analysis with vector error correction was introduced that the rather obvious term magnitude or scalar measurements became more popular.


OBJECTIVES

- Introduce Scalar Measurement Concepts
- Explain Network Characterization Technique in the Microwave Frequency Range
- Discuss Practical Measurement Applications

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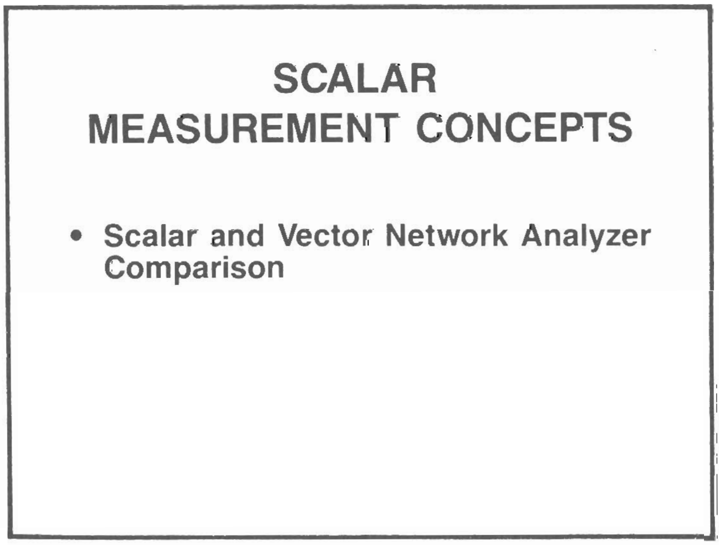
The objectives of this presentation are:

To explain the difference between Scalar and Vector Network Analyzer concepts.

Introduce a variety of network characterization techniques in the microwave frequency range.

Discuss practical scalar measurement applications.


SCALAR MEASUREMENT CONCEPTS

- Scalar and Vector Network Analyzer Comparison

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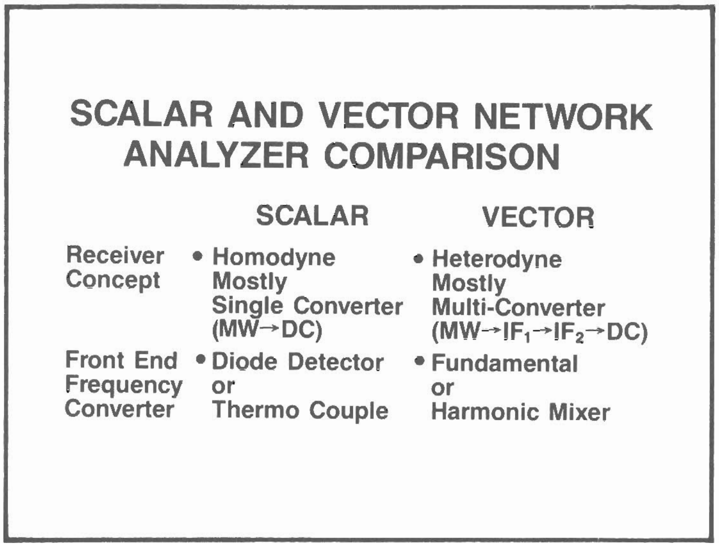
## 1. SCALAR MEASUREMENT CONCEPTS

The fundamental difference between Vector and Scalar Network Analyzers stems from different receiver concepts applied. All the other systems characteristics are a direct or indirect result of this.

## 1.1 SCALAR AND VECTOR NETWORK ANALYZER COMPARISON

The Scalar Analyzer Receiver measures the magnitude of the microwave test signal to be measured by converting it into a low frequency AC or DC signal by means of a thermo electrical effect or a diode homodyne process. (1)

Most Vector Network Analyzers, on the other hand, are heterodyne receivers with multiple frequency converters based on fundamental or harmonic mixing with a local oscillator signal. (2)



SCALAR AND VECTOR NETWORK ANALYZER COMPARISON

| | SCALAR | VECTOR |
|---|---|---|
| Receiver Concept | • Homodyne Mostly Single Converter ($MW \rightarrow DC$) | • Heterodyne Mostly Multi-Converter ($MW \rightarrow IF_1 \rightarrow IF_2 \rightarrow DC$) |
| Front End Frequency Converter | • Diode Detector or Thermo Couple | • Fundamental or Harmonic Mixer |

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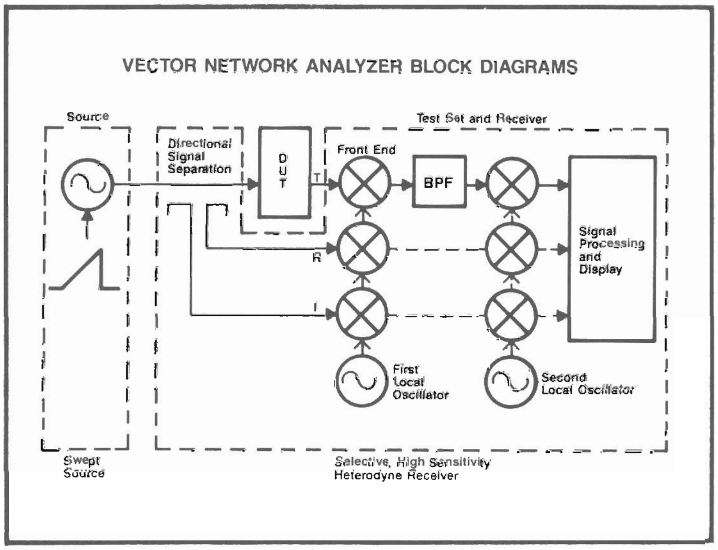
Subsequent filtering allows reducing the processing bandwidth and therefore improving the signal-to-noise ratio which ultimately leads to improved sensitivity and dynamic range. Furthermore, the narrowband receiver characteristic suppresses harmonic and spurious signals at other frequencies.

The Vector Analyzer then measures the down converted microwave signal characteristics in terms of amplitude and phase at a low intermediate frequency (IF).



VECTOR NETWORK ANALYZER BLOCK DIAGRAMS

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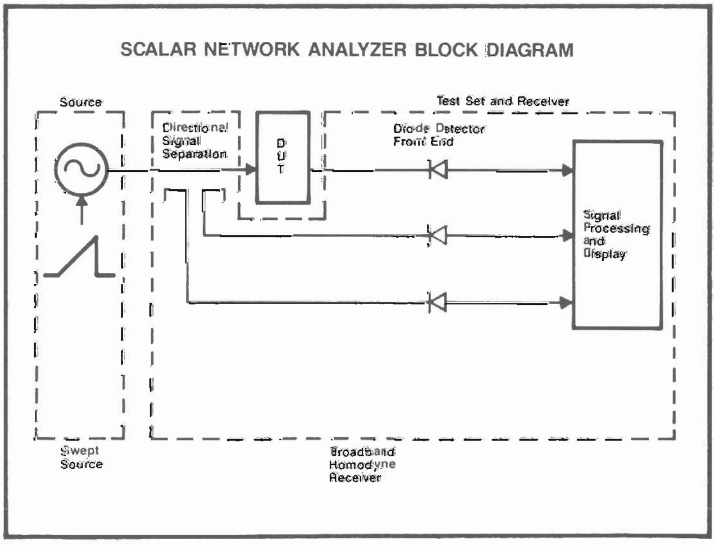
In contrast, Scalar Network Analyzers with diode detectors as frequency (down) converters are inherently broadband receivers. (4)

This gives them the capability to measure any signal in the entire frequency band instantaneously. A feature which is important for characterizing frequency translating components (mixers), or when high frequency agility is required. The trade offs are: a) less sensitivity mainly because of the broadband noise and lower conversion efficiency of the diode converter and b) limited rejection of undesirable signal components. (5)



SCALAR NETWORK ANALYZER BLOCK DIAGRAM

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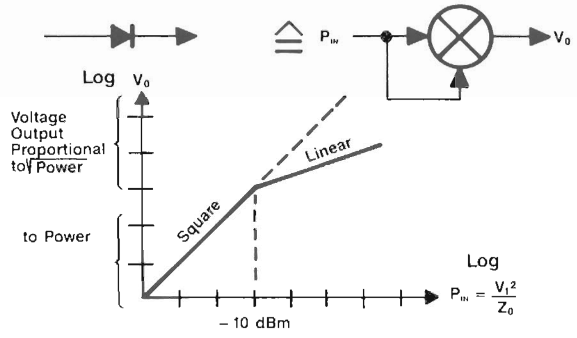
## DIODE DETECTOR AS FREQUENCY CONVERTER



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## SCALAR AND VECTOR NETWORK ANALYZER COMPARISON

| | SCALAR | VECTOR |
|---|---|---|
| **Basic Characteristics** | • Broad Band | • Narrow Band |
| | • Very Frequency Agile | • High Selectivity |
| | • Lower Sensitivity (≤ – 60 dBm) | • High Sensitivity (≤ – 100 dBm, Wide Dynamic Range) |
| | • Self-Convolving Mixer Without Local Oscillator | • Synchronously Tuned Local Oscillator |
| | • Lower Cost & Performance | • Higher Cost & Performance |

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## SCALAR AND VECTOR NETWORK ANALYZER COMPARISON

| | SCALAR | VECTOR |
|---|---|---|
| **Fundamental Measurements** | • Signal Magnitude or Magnitude Squared (Power) | • Signal Amplitude and Phase |
| **Accuracy** | • Scalar Error Correction Only | • Elaborate Vector Error Correction |

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A simple way to model such a configuration is a mixer multiplier circuit with both RF and LO inputs connected together. At high RF power levels, the signal at the LO input is sufficient to convert the RF signal proportionally (with a nominal conversion loss) to the output of the mixer.

This operating area is called linear (conversion) for the diode detector and an incremental change at the input generates a proportional change in (detected) output signal.

As the RF signal is reduced, the LO component in the model drops and the conversion efficiency is reduced until the RF and LO only contribute in a multiplicative way to the output signal. Therefore at low signal levels, an incremental RF input signal drop translates into twice the drop of detected signal at the output. This diode operating area is called square law (conversion) since the detected signal is proportional to the product of RF and LO which is RF-squared.

When used as a Scalar Analyzer front end, the diode square law characteristic is extended by appropriate signal processing over the entire operating range (dynamic range) in order to maintain a calibrated display.

Having the signal vectors available in complex form (amplitude and phase) allows the application sophisticated error correction techniques which dramatically reduces measurement ambiguities. (3)

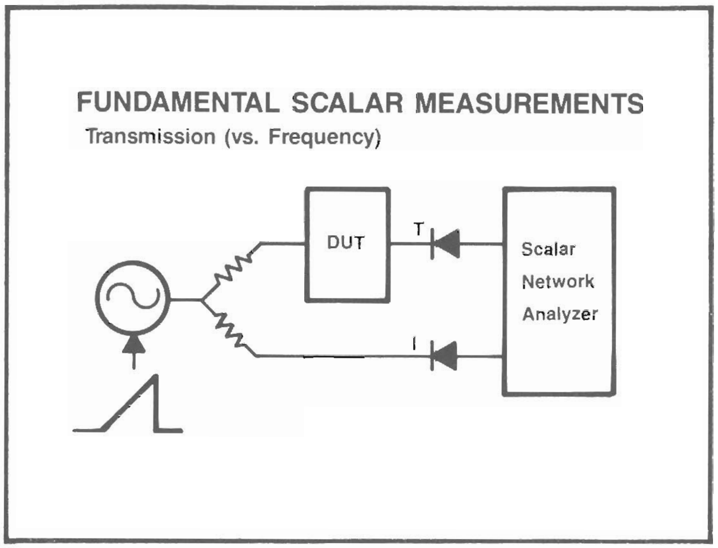
However, the improved performance of a Vector Network Analyzer does not come for free and the hardware cost of the heterodyne structure with the synchronously tuned local oscillator and the additional processing capability adds substantially to the cost of this measurement system.

## 1.2 FUNDAMENTAL SCALAR MEASUREMENTS

Let's quickly review the two most common scalar measurement concepts:

1. Transmission
2. Reflection

as a function of frequency. (6)(7)



FUNDAMENTAL SCALAR MEASUREMENTS

Transmission (vs. Frequency)

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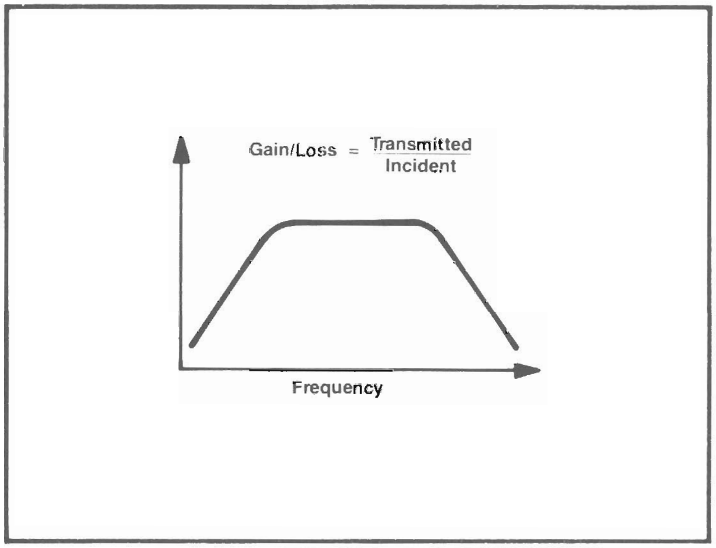
### TRANSMISSION:

The swept source provides a test signal over the frequency range of interest which is applied to the device under test (DUT) and the transmitted signal (T) is measured by the Scalar Analyzer. Since we are usually interested in Transmission Gain or Loss, the incedent signal (I) is measured and compared with the transmitted signal and the signal ratio is computed as shown in the graph below.

As an example, the transfer function or gain of a band-pass filter is displayed as a function of frequency.



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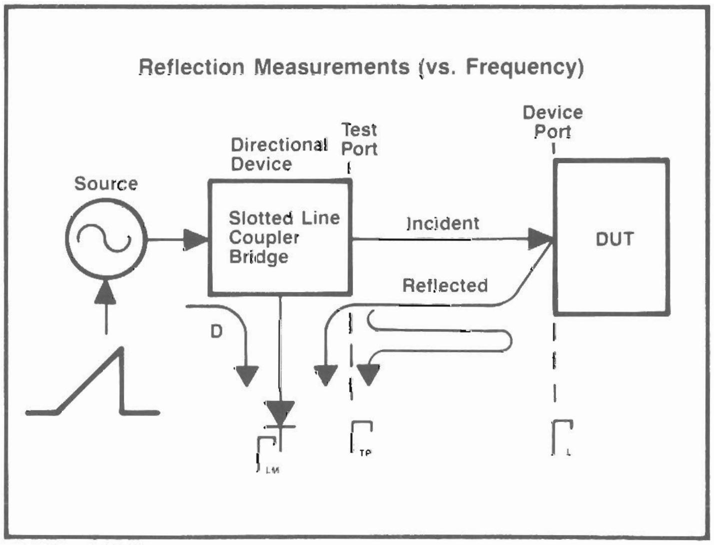
### REFLECTION:

In a reflection measurement, the incident and reflected signal are separated by a directional device (bridge coupler, etc.) and measured either separately, or as a superposition in form of a standing wave pattern (slotted line).



Reflection Measurements (vs. Frequency)

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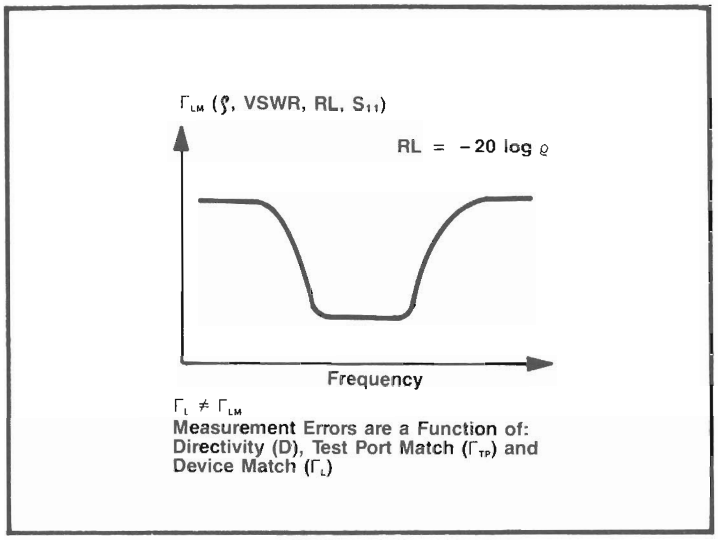

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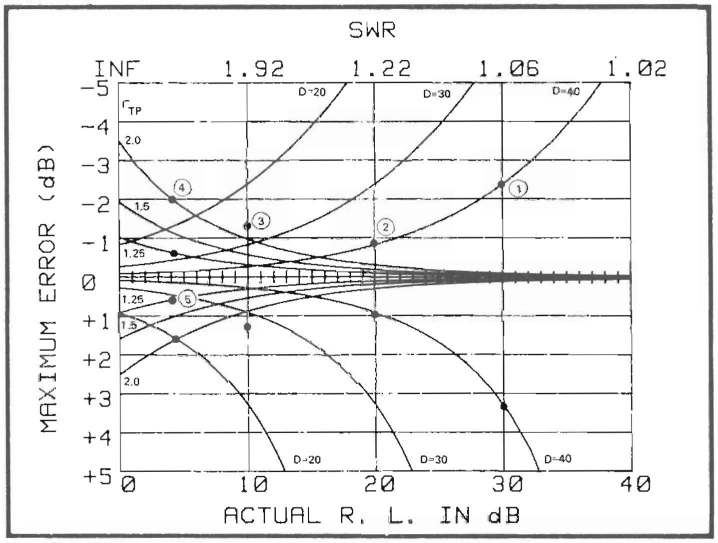

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| **Examples:** | **D dB** | **$\Gamma_{TP}$ VSWR** | **$\Gamma_{LM}$** | **Error Ambiguity** |
|---|---|---|---|---|
| ① $\Gamma_L$ = 30 dB | 40 | * | 30 | +3.5 −2.5 dB |
| ② 20 dB | 40 | * | 20 | +1.0 − .9 dB |
| ③ 10 dB | 40 | ≤2.0 | 10 | +1.3 −1.2 dB |
| ④ 4 dB | 30 | ≤2.0 | 4 | +2.5 −2.0 dB |
| ⑤ 4 dB | 40 | ≤1.1 | 4 | ± .4 dB |

**For High (≥20 dB) Return Loss Measurements Directivity Dominates, for Low (≤10 dB) R.L. the Test Port Match Dominates**

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The reflection coefficient, gamma is then computed by either forming the ratio of reflected (R) over incident (I) signal or by converting the standing wave ratio as shown later.

## ACCURACY CONSIDERATIONS:

Unfortunately, a perfect separation of incident and reflected signal is not possible. A part of the incident signal, attenuated by the directivity (D) of the directional device will be present also. Furthermore, since the directional device does not have a perfect port match, some of the reflected signal (gamma-L) gets re-reflected (gamma-TP). Mainly, these two error terms cause the measured reflection coefficient (gamma-LM) of the device under test to be different than the actual term (gamma-L).

The chart and the table show how we can estimate the measurement ambiguity caused by the directivity (D) and the test port match (gamma-TP) as a function of the value of reflection coefficient to be measured (gamma-L).

For high returnloss measurements (gamma-L ≥20dB), the directivity (D) dominates the ambiguity and for lower returnloss (gamma-L ≤10dB), the test port match becomes the major contributor.

## 2. SCALAR NETWORK CHARACTERIZATION TECHNIQUES

### 2.1 OVERVIEW

A Scalar Analyzer is really a generalized stimulus response test set capable of doing a wide variety of network characterization tasks.

**ADVANCED**

**NETWORK CHARACTERIZATION TECHNIQUES: AN OVERVIEW**

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Frequency response measurements are probably the most popular for linear networks.

Other networks may exhibit signal level dependent parameters like amplifiers.

**MEASUREMENT DOMAINS**

- Frequency Response (or Versus Frequency) Measurements
- Network Characterization Versus Signal Level
- Frequency, Time and Impedance Domain Characterization

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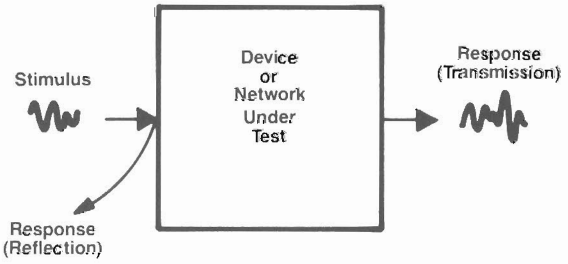
Another group of stimulus response measurements allows us to characterize networks in a time/distance or impedance domain.

**STIMULUS → RESPONSE CONCEPT**



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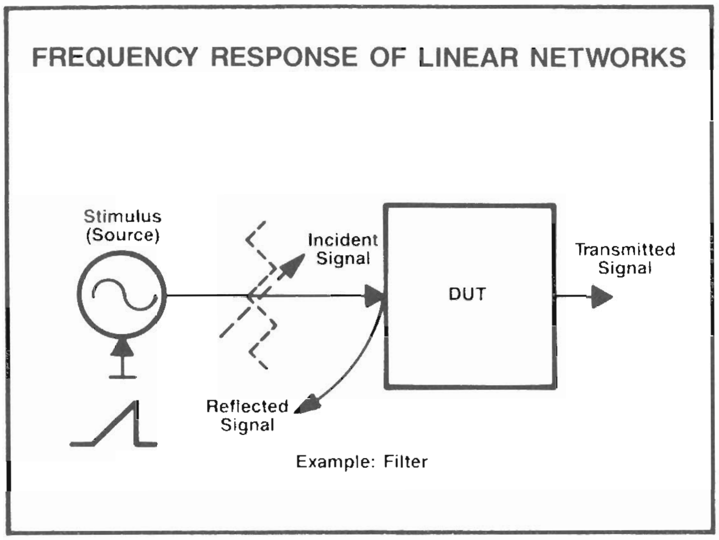
## 2.2 FREQUENCY RESPONSE OF LINEAR NETWORKS

We already covered the most important scalar measurements (transmission and reflection) of this class of networks.


FREQUENCY RESPONSE OF LINEAR NETWORKS

Example: Filter

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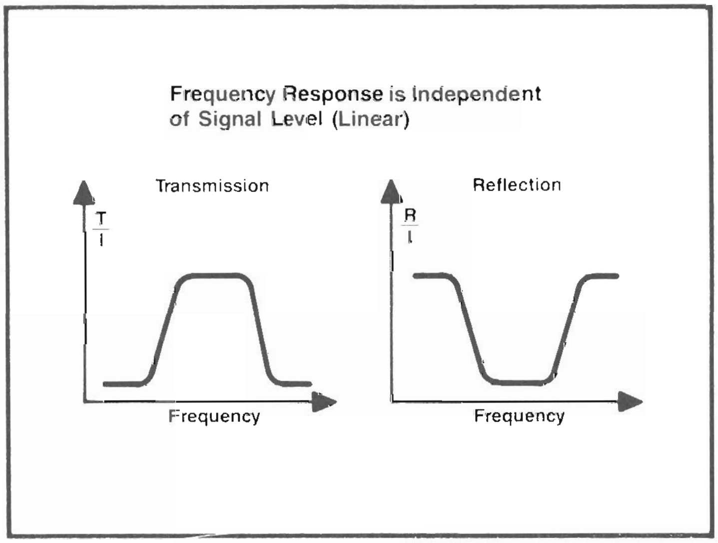
An additional selection of related measurements is listed below.


Frequency Response is Independent of Signal Level (Linear)

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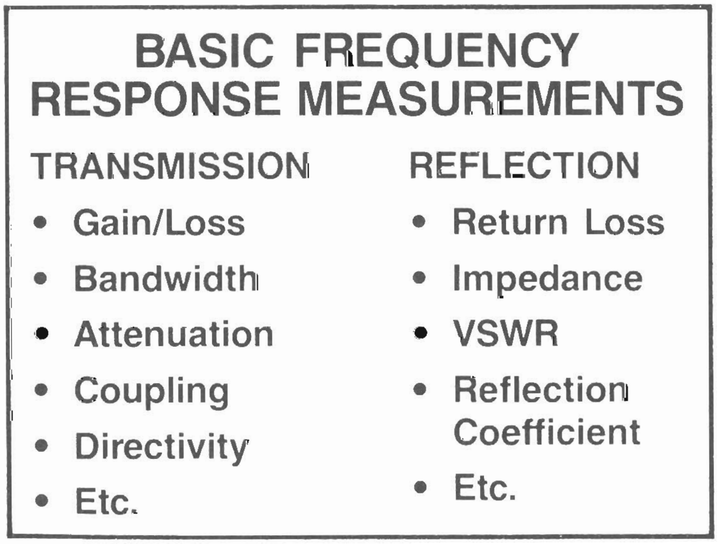
These parameters are either directly derived from the basic transmission or reflection measurements like bandwidth and directivity or are computed from the fundamental measurement like VSWR from returnloss either internally to the Analyzer, or externally with a controller/computer.


BASIC FREQUENCY RESPONSE MEASUREMENTS

| TRANSMISSION | REFLECTION |
|---|---|
| • Gain/Loss | • Return Loss |
| • Bandwidth | • Impedance |
| • Attenuation | • VSWR |
| • Coupling | • Reflection Coefficient |
| • Directivity | • Etc. |
| • Etc. | |

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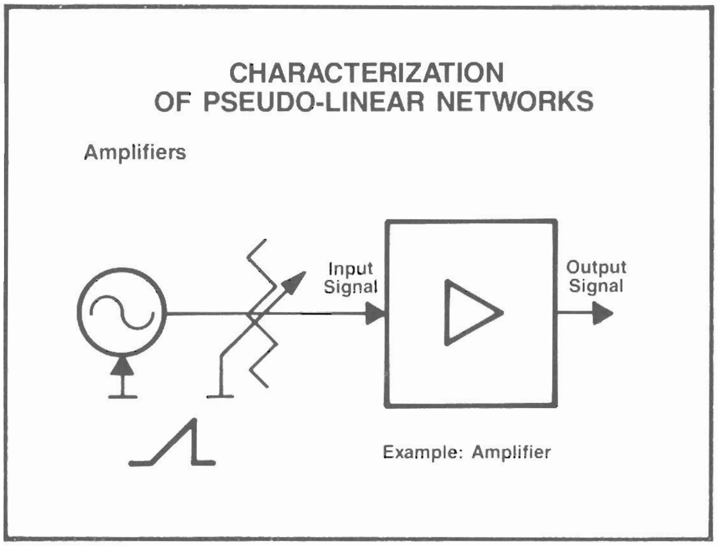
## 2.3 CHARACTERIZATION OF PSEUDO LINEAR NETWORKS

For example, an amplifier is a network where some of the key parameters may depend on the signal level. In that case, the frequency response has to be measured for various power levels to fully characterize its behavior.


CHARACTERIZATION
OF PSEUDO-LINEAR NETWORKS

Amplifiers

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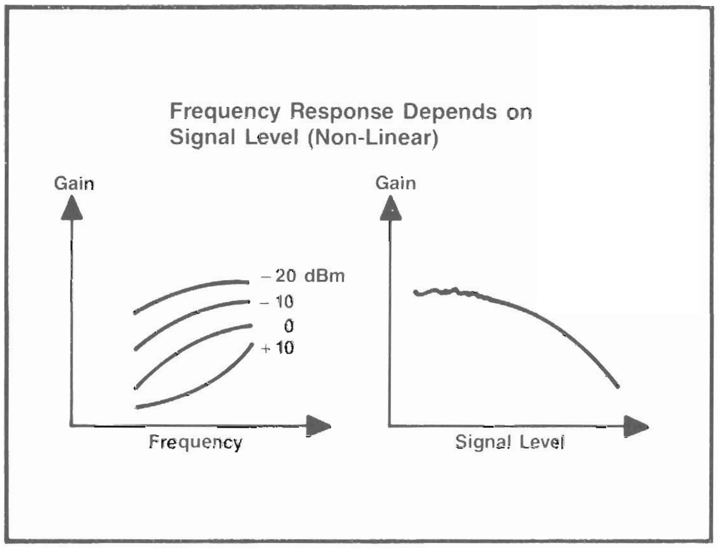
Furthermore, it is often important to measure the gain as a function of the input or output signal to establish the maximum power gain or the compression points.


Frequency Response Depends on
Signal Level (Non-Linear)

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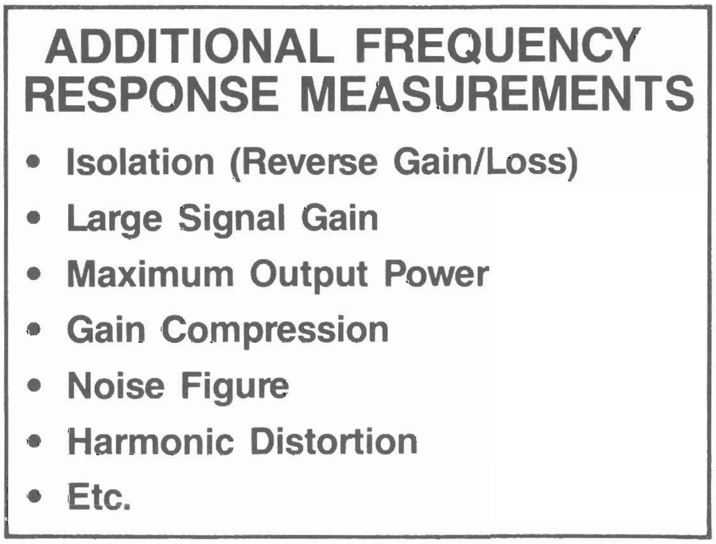
Here is a set of additional measurements that might be required to better characterize this class of networks.


**ADDITIONAL FREQUENCY RESPONSE MEASUREMENTS**

- Isolation (Reverse Gain/Loss)
- Large Signal Gain
- Maximum Output Power
- Gain Compression
- Noise Figure
- Harmonic Distortion
- Etc.

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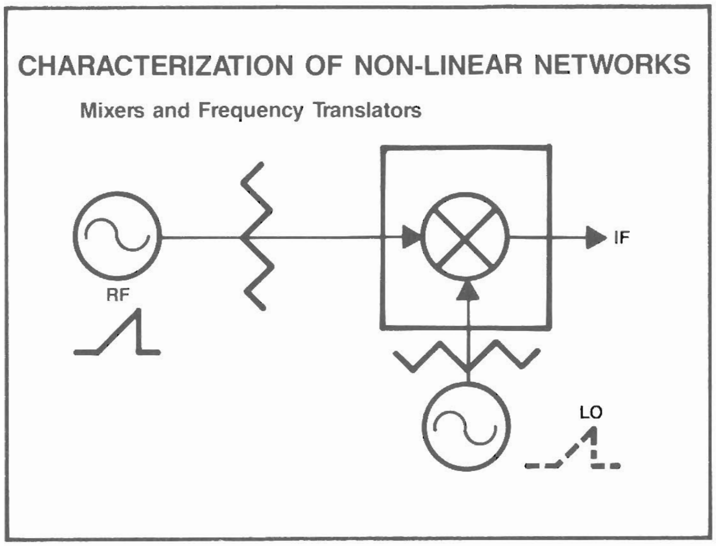

CHARACTERIZATION OF NON-LINEAR NETWORKS

Mixers and Frequency Translators

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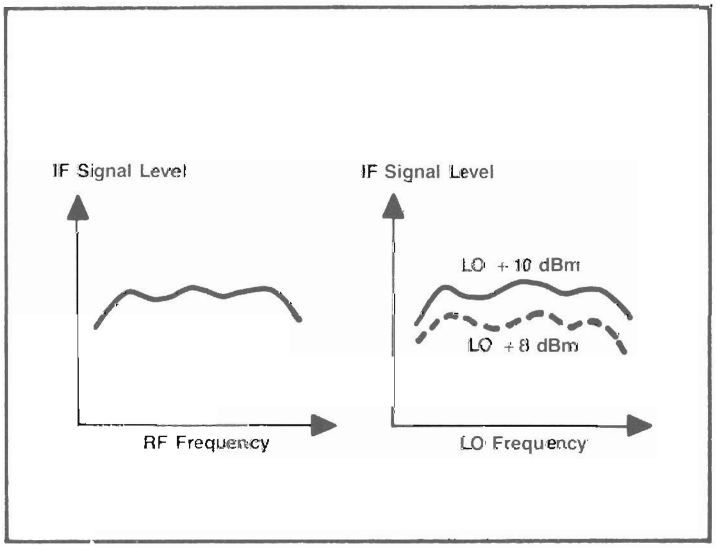
## 2.4 CHARACTERIZATION OF NON-LINEAR NETWORKS

Mixers and frequency translators are usually considered non-linear networks even though their frequency response is measured as if they were linear components.



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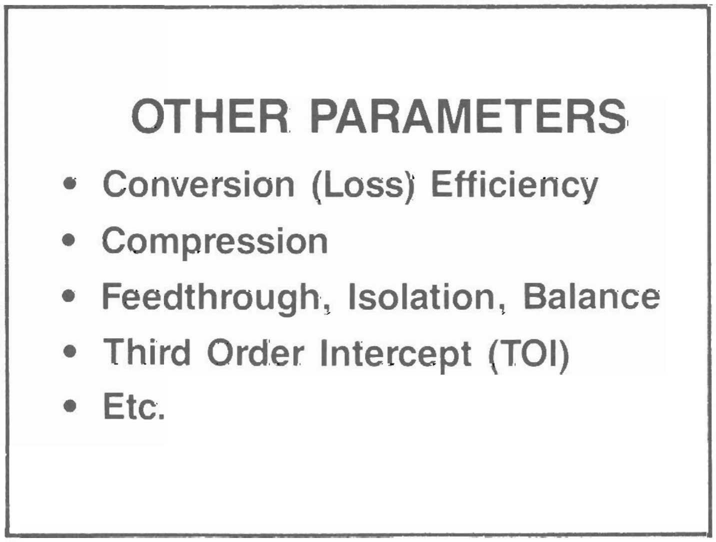
The flatness of the conversion from RF to IF port (as a function of RF or LO frequency), as well as the frequency response for various LO drive levels has to be established.



OTHER PARAMETERS

- Conversion (Loss) Efficiency
- Compression
- Feedthrough, Isolation, Balance
- Third Order Intercept (TOI)
- Etc.

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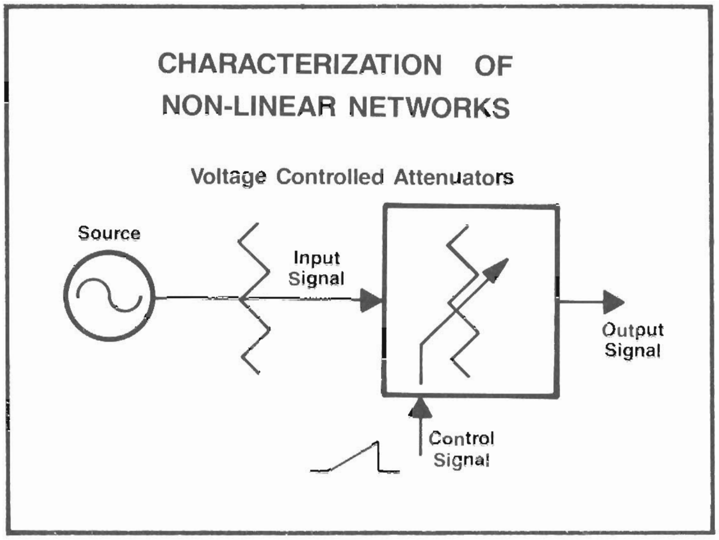
A scalar network analyzer is the ideal measurement tool to characterize these components because of the inherent broadband characteristic of the receiver.

A different example of a non-linear network is shown in the following slides. A voltage controlled attenuator (or modulator) is characterized as a function of the control signal.



CHARACTERIZATION OF NON-LINEAR NETWORKS

Voltage Controlled Attenuators

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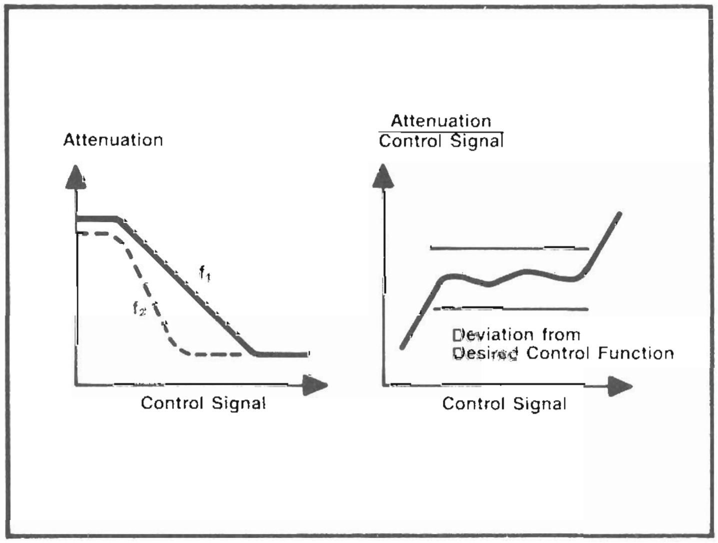
The figure shows attenuation characteristic for two different frequencies as well as a deviation from the desired control function plot.



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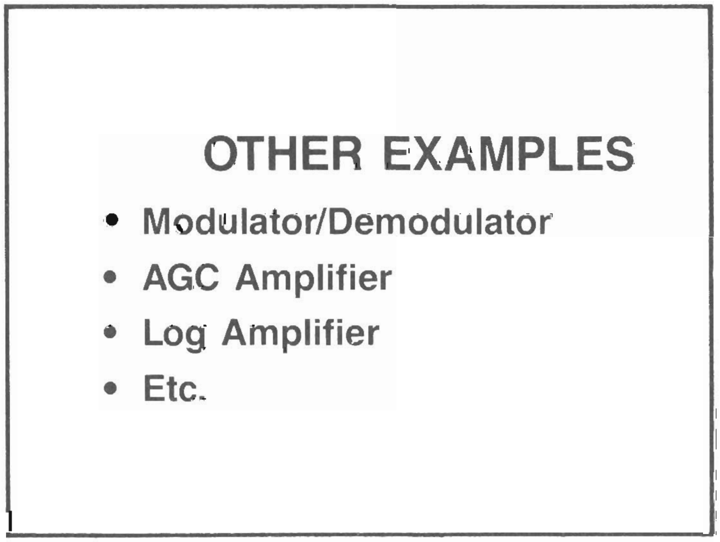
Additional examples of components which can be characterized in a similar fashion are listed below.



OTHER EXAMPLES

- Modulator/Demodulator
- AGC Amplifier
- Log Amplifier
- Etc.

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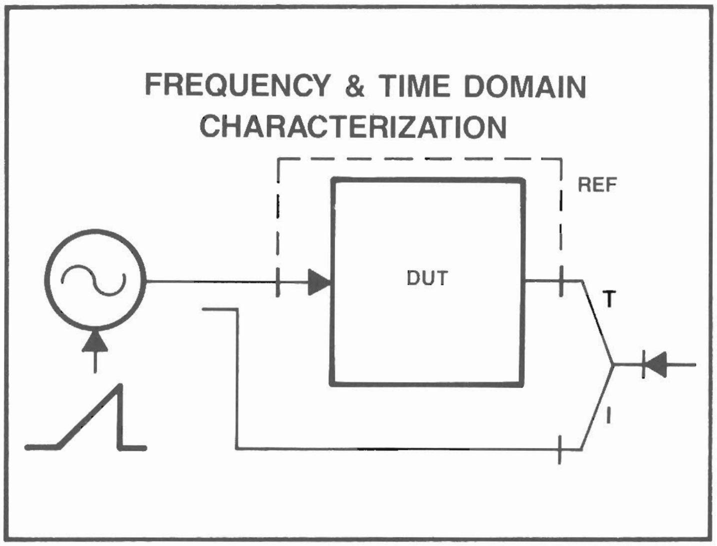
## 2.5 FREQUENCY AND TIME DOMAIN CHARACTERIZATION



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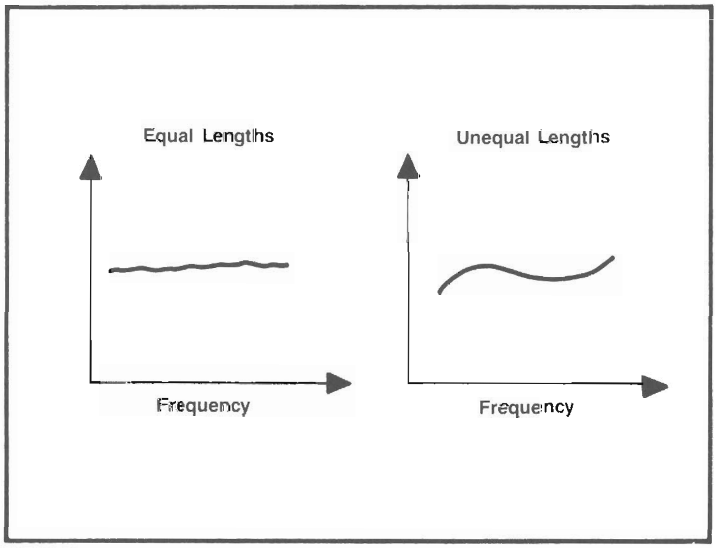
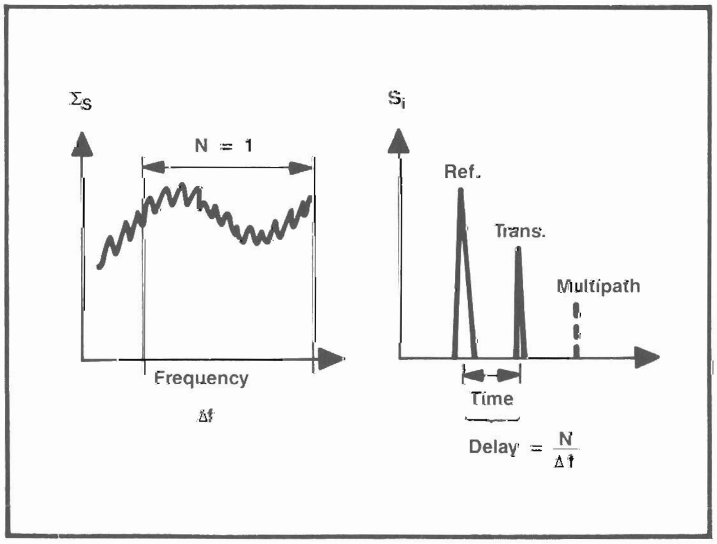
The Scalar Analyzer concept (homodyne receiver) lends itself nicely to do time and distance domain characterization via frequency domain measurements. An inverse Fourier transform computation is used to give the time domain display.



The basic operating principle is explained below. The diode detector convolves the transmitted (T) and the reference (REF.) signal resulting in a ripple pattern over the frequency span of interest due to the phasing of the two microwave vectors.

If the reference and transmitted path lengths are equal, the resulting swept response would be a flat trace as there is no time delay between the two signals. When one path length is longer, a ripple pattern will be exhibited.



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The number of envelop periods (N) divided by the frequency change (delta-f) will indicate the delay of the device under test with respect to a reference calibration.

Higher order ripples will occur if the signal is reflected and travels through the network again or when multipath transmission occurs through or around the device under test.

The major applications for this measurement principle are listed here.

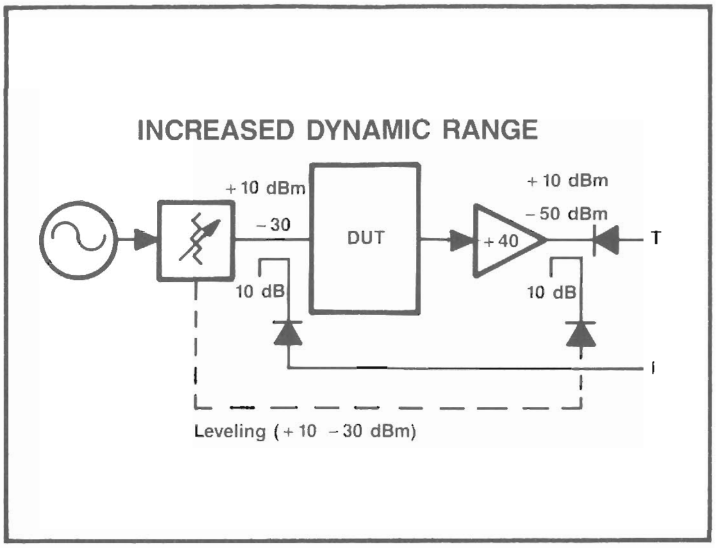
### MEASUREMENT APPLICATIONS

- Time Delay Measurements
- Fault Location
- Multipath Transmission
- Etc.

## 3. PRACTICAL MEASUREMENT APPLICATIONS

### PRACTICAL MEASUREMENT APPLICATIONS

## 3.1 INCREASED DYNAMIC RANGE MEASUREMENTS



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As previously mentioned, scalar analyzers have usually less dynamic range than vector analyzers do. However, there are ways to significantly extend the measurement range by considering the following test set-up. (8)

Instead of only utilizing the dynamic range of our receiver channel (T), the incident signal (I) is also varied as a function of the attenuation of the device under test by means of the leveling loop.

**SIGNAL LEVELS AS A FUNCTION OF DUT ATTENUATION:**

| | DUT Loss | Incident | Transmitted |
|---|---|---|---|
| ① | 0 dB | -40 dBm | +10 dBm |
| | 20 | -20 | +10 |
| ② | 40 | 0 | +10 |
| | 60 | 0 | -10 |
| | 80 | 0 | -30 |
| ③ | 100 | 0 | -50 |

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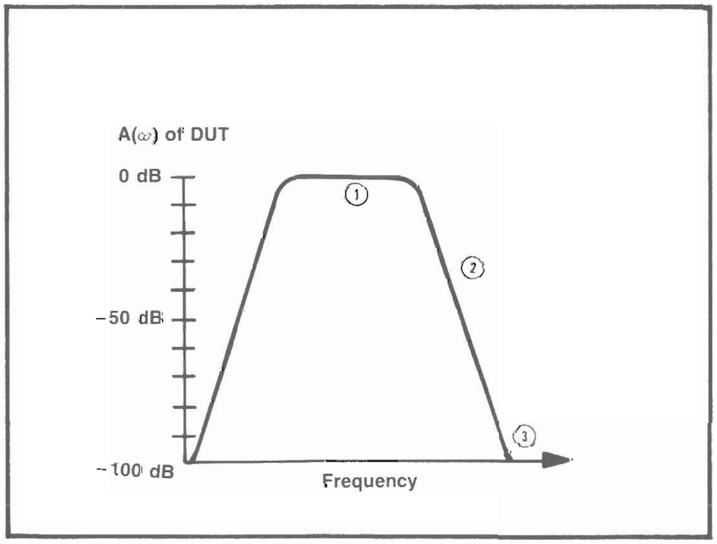
For high attenuation, the amplifier in the test path brings the signal level up by 40 dB at the same time the source puts out its maximum power (+10 dBm).



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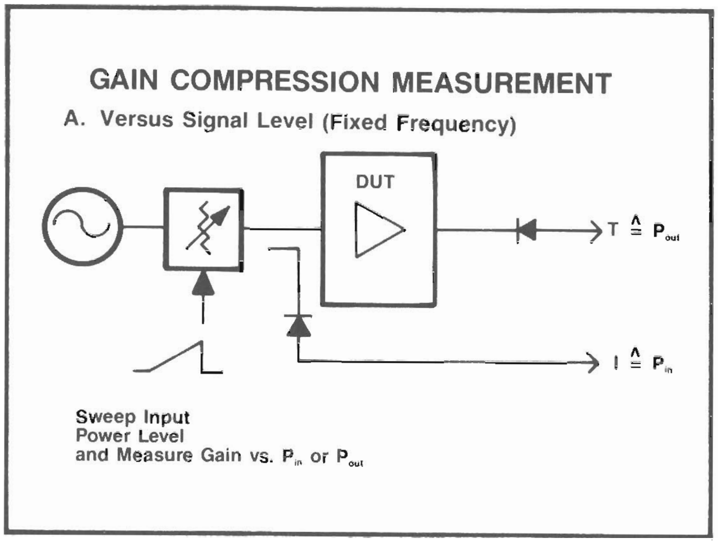
For low attenuation of the device under test, the (amplified) transmitted signal rises and simultaneously the source power is reduced via leveling loop not to exceed the maximum measureable output signal.

The ratio T/I therefore varies from +50 to -50 dB thus displaying 100dB of dynamic range.

## 3.2 GAIN COMPRESSION MEASUREMENTS ON AMPLIFIERS

The next example shows an application where the network has to be characterized as a function of signal level to establish the maximum undistorted output power or at what input (or output) level the gain drops by a given amount. For example, by 1 dB which is called the 1dB compression point.



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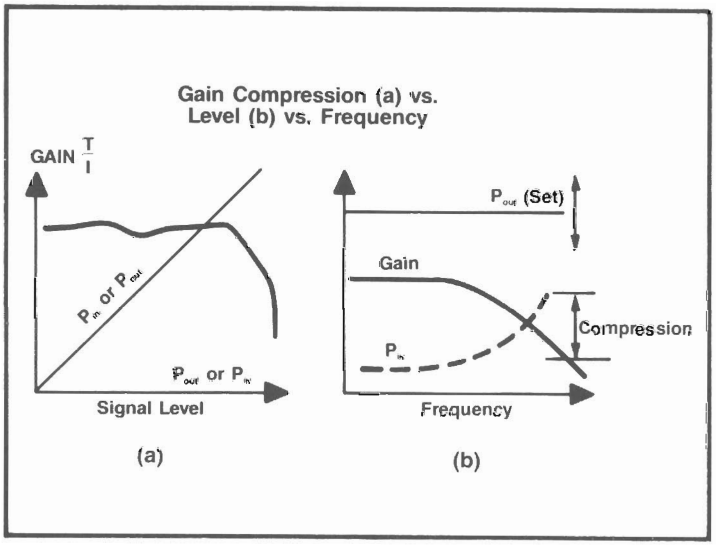
The test is done in two steps:

a) as a function of signal level at a constant frequency, and
b) as a function of frequency at a certain output level.



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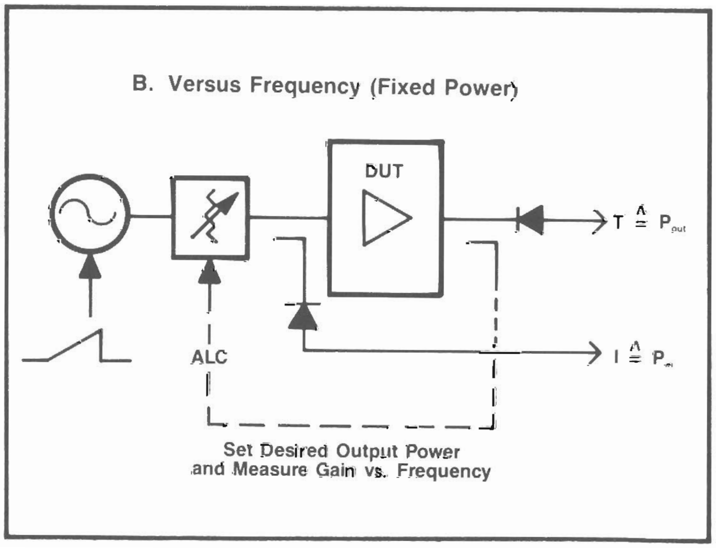
The set-up for the latter measurement is shown here and includes the leveling loop to establish a desired power level at the output. The display indicates gain compression as a function of frequency for this set output power.



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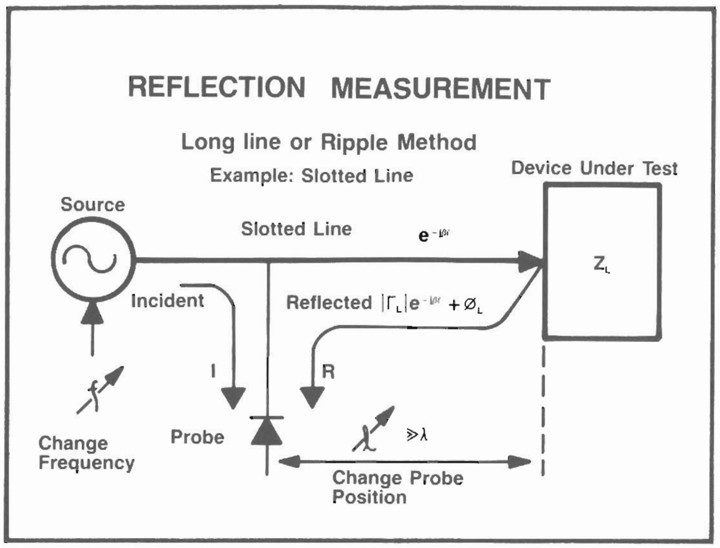

## REFLECTION MEASUREMENT

Long line or Ripple Method

Example: Slotted Line

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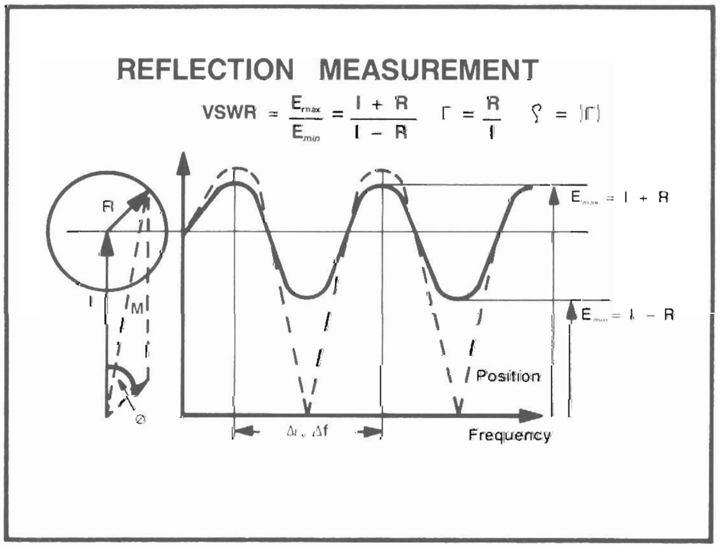

## REFLECTION MEASUREMENT

$$\mathrm{VSWR} = \frac{E_{max}}{E_{min}} = \frac{I+R}{I-R} \qquad \Gamma = \frac{R}{I} \qquad \rho = |\Gamma|$$

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$$M = \sqrt{I^2 + R^2 - 2IR\cos\varnothing}$$

$$\varnothing = 2\beta l - \varnothing_L$$

$$\beta = \frac{360^\circ \times \text{Frequency}}{\text{Propagation Velocity}}$$

$$\Delta l\,[\text{cm}] = \frac{v}{f} = \frac{15\,[\text{cm}]}{\Delta f\,[\text{GHz}]}$$

$$\Delta f\,[\text{GHz}] = \frac{v}{l} = \frac{15\,[\text{cm}]}{\Delta l\,[\text{cm}]}$$

$$\underset{\text{(Round Trip)}}{\Delta t\,[\text{ns}]} = \frac{2\Delta l}{v} = \frac{\Delta l\,[\text{cm}]}{15\,[\text{cm}]} = \frac{2}{\Delta f\,[\text{GHz}]}$$

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## 3.3 REFLECTION MEASUREMENT WITH THE LONG LINE OR RIPPLE TECHNIQUE

As shown in the first paragraph, scalar reflection measurements are usually taken by inserting a directional bridge or coupler as a signal separation device in front of the device under test. Comparing the incident (I) and reflected (R) signal leads to the measured reflection coefficient of the network, which includes the ambiguities due to directivity (D) and test port match of the set up.

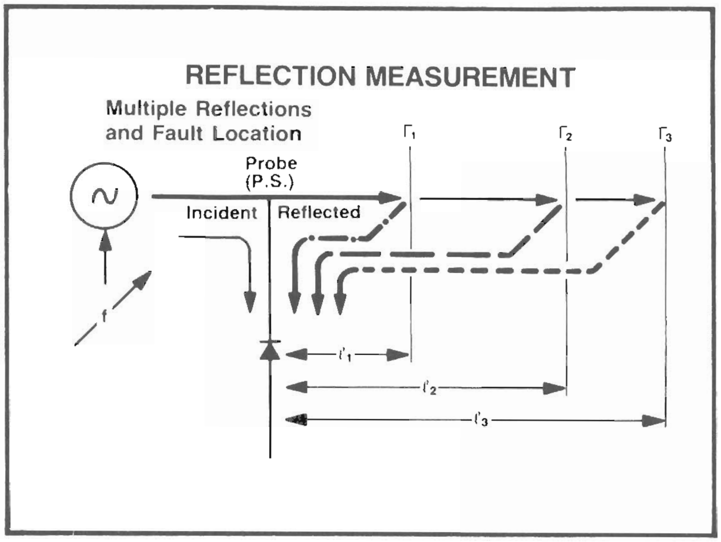
In order to understand some of the improvements and new developments in scalar measurements, it may be beneficial to digress back to the slotted line reflection measurements as shown here.

The reflection coefficient in this case, is determined by measuring the standing wave pattern along the transmission line. Unlike in the case of the reflection measurement with a directional bridge (or coupler), this method is basically capable of measuring the complex reflection coefficient gamma (with the appropriate calibration and some computational effort).

Because of the duality between standing wave patterns versus frequency and length, this method can be readily expanded to measure discontinuities (reflections) in cables when the frequency is varied. By scaling the electrical length (l) with the appropriate propagation velocity, the location of the discontinuity can be calculated (e.g., open end of cable).

## 3.4 MULTIPLE REFLECTIONS AND FAULT LOCATION

The measurement concept just discussed can be expanded to resolve multiple reflections. Depending on the location and size of discontinuities, the scalar analyzer will show a superposition of ripple patterns which can be analyzed by extracting the indivivual mismatch ripples.


REFLECTION MEASUREMENT

Multiple Reflections
and Fault Location

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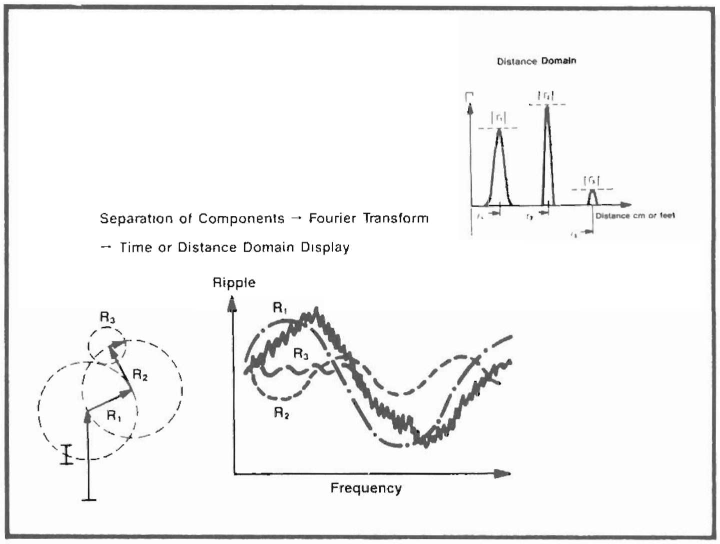
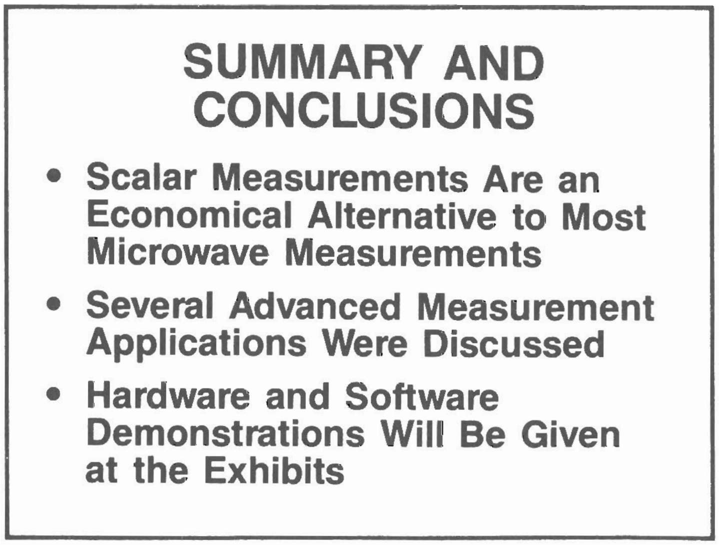
The inverse Fourier transform (with the approprpriate windowing) will convert the ripple pattern in individual impluse functions spaced according to the electrical length of the position of the discontinuites along the propagation path.

The resolution in the time or distance domain is obviously inversely proportional to the higher frequency component of the test signal (@ 20 GHz ≙ 1.5cm or .05ns).


Separation of Components → Fourier Transform
→ Time or Distance Domain Display

2656 2657

In summary, scalar measurements were presented as an economical alternative for many microwave and RF measurements. We covered several general and some specific applications, and we will demonstrate some examples with the associated hardware and software at the exhibits. (9)(10)


SUMMARY AND CONCLUSIONS

- Scalar Measurements Are an Economical Alternative to Most Microwave Measurements
- Several Advanced Measurement Applications Were Discussed
- Hardware and Software Demonstrations Will Be Given at the Exhibits

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