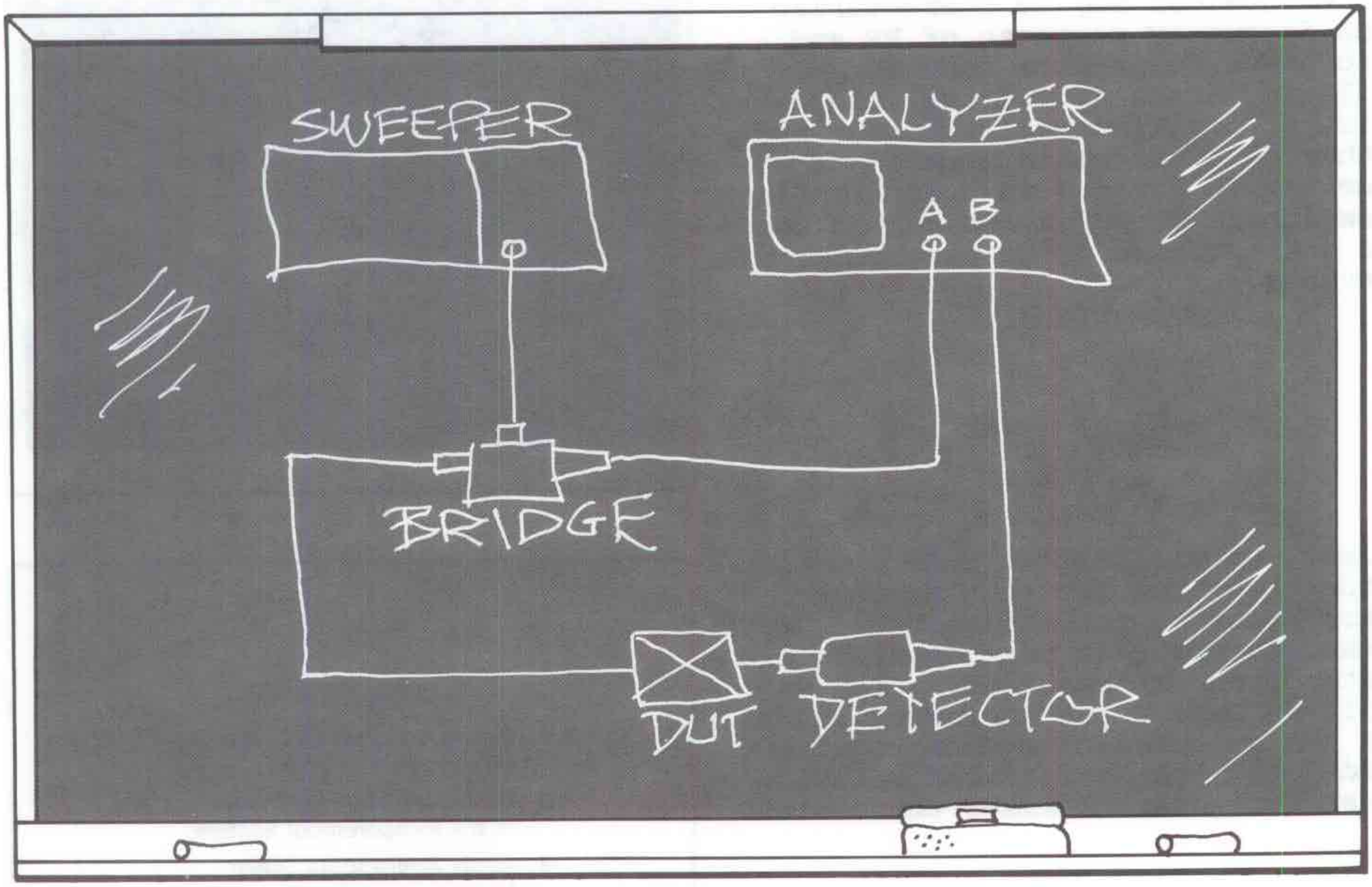
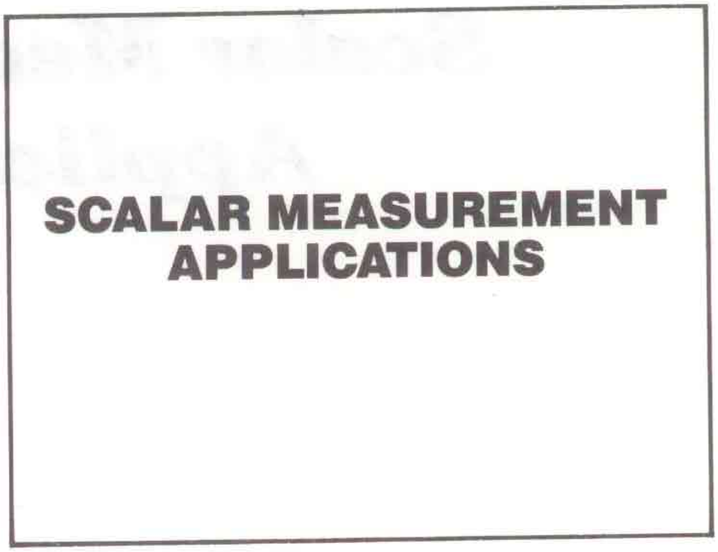
Scalar Measurement Applications



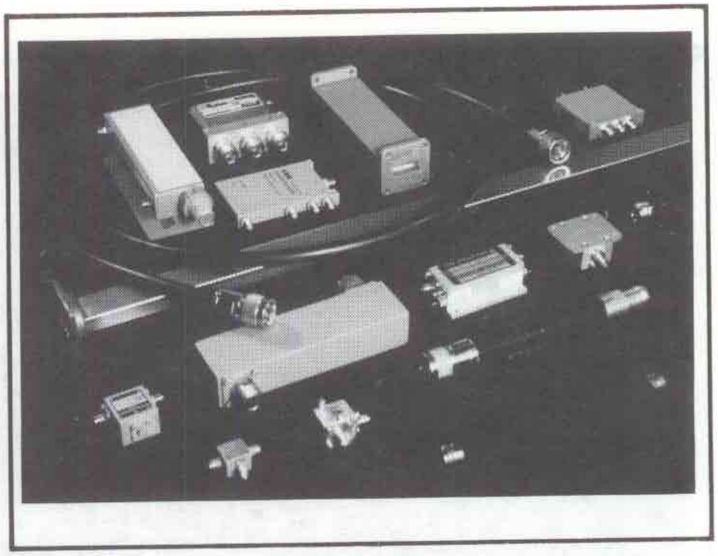
Now that we are familiar with network analysis and some of the measurement techniques, we are now equipped to apply these techniques to real applications.



SCALAR MEASUREMENT APPLICATIONS

3205

Scalar network measurements provide an economical way to characterize the frequency response of RF and microwave components such as filters, attenuators, amplifiers, mixers, oscillators, antennas, and other devices. This section of the seminar is devoted to understanding how scalar measurements can be used to characterize these particular devices.



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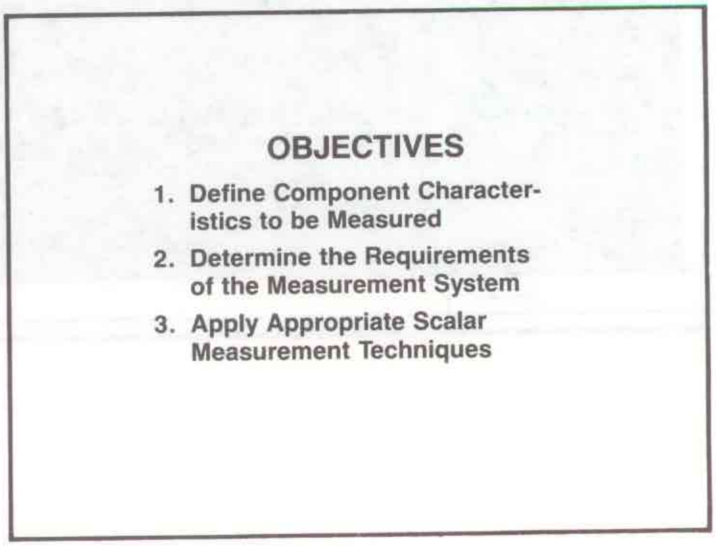
First, we will define and understand the function of some particular components to be measured and what parameters we are interested in measuring. Then we will determine the characteristics of the measurement system required, and apply the measurement solution that best characterizes the device.



OBJECTIVES

1. Define Component Characteristics to be Measured
2. Determine the Requirements of the Measurement System
3. Apply Appropriate Scalar Measurement Techniques

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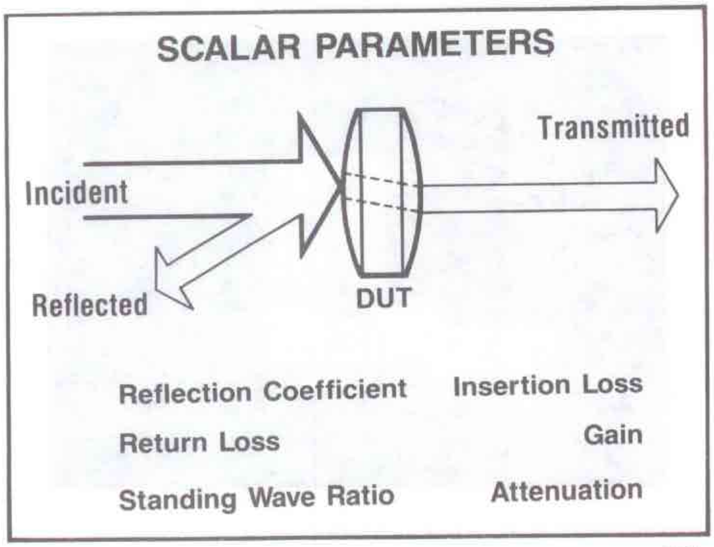


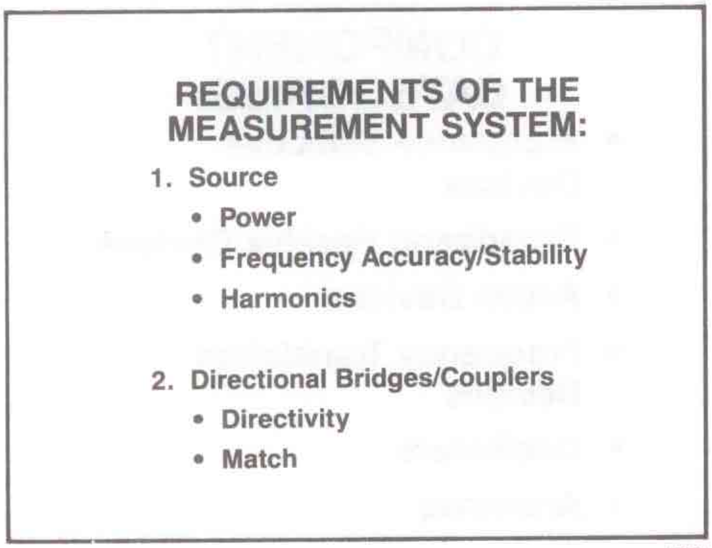
SCALAR PARAMETERS

Reflection Coefficient
Return Loss
Standing Wave Ratio

Insertion Loss
Gain
Attenuation

2934

These scalar measurement parameters were defined in the previous section. Reflection coefficient, return loss, and standing wave ratio are used to describe reflection from the device, and insertion loss, gain, and attenuation are used to describe transmission through the device. Swept power measurements can also be made as we will see in some examples.



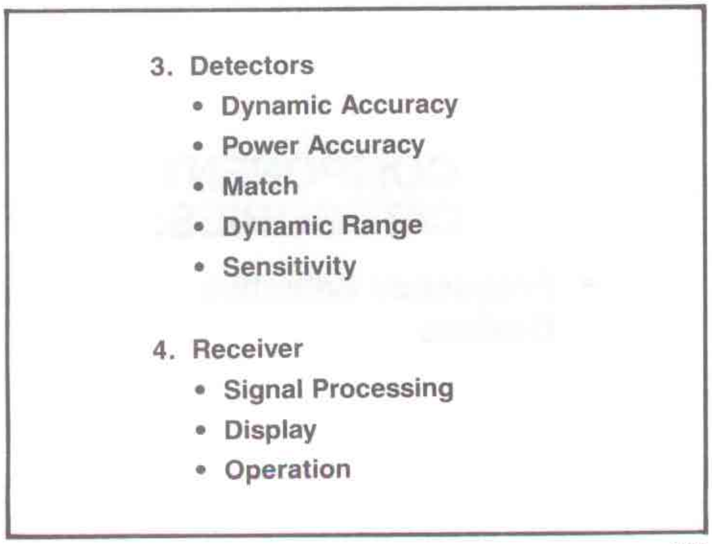
REQUIREMENTS OF THE MEASUREMENT SYSTEM:

1. Source
   - Power
   - Frequency Accuracy/Stability
   - Harmonics
2. Directional Bridges/Couplers
   - Directivity
   - Match

3208

The specific component characteristics being measured will dictate what requirements we place on the four parts of the scalar measurement system. Some measurements have very stringent requirements that must be met by expensive or complex measurement equipment. Other measurements with less stringent requirements can be accomplished without added expense or complexity.

The source must not only provide enough power, but must also have sufficient frequency accuracy and harmonic performance. The signal separation devices must have high directivity and good impedance match to avoid significant measurement errors.

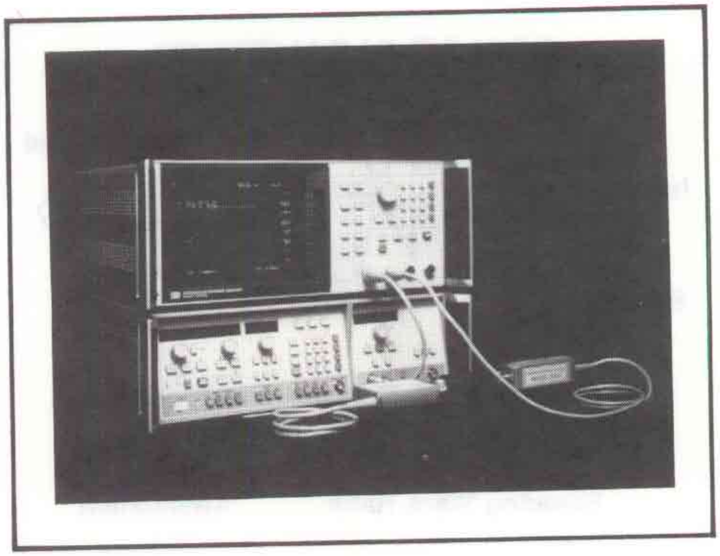


3. Detectors
   - Dynamic Accuracy
   - Power Accuracy
   - Match
   - Dynamic Range
   - Sensitivity
4. Receiver
   - Signal Processing
   - Display
   - Operation

3209

The detectors should be accurate and their response should be independent of power level (dynamic accuracy). The detectors must not introduce significant reflections, and the dynamic range and sensitivity must be sufficient to characterize the component.
The receiver must process the received data and display the necessary measurement information clearly. The receiver should also be easy to operate so that accurate measurements can be made quickly.

When measuring any component, the requirements of the measurement system must be evaluated. In this discussion, we will see how these system requirements affect the measurement of specific device characteristics.



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There are many types of components that can be measured using scalar network analysis. For the purposes of this discussion, we have placed these devices into six categories. Devices in each one of these categories exhibit similar characteristics and place similar requirements on the measurement system.

COMPONENT CATEGORIES:

- Frequency Selective Devices
- Broadband Passive Devices
- Active Devices
- Frequency Translation Devices
- Oscillators
- Antennas

3211

Let's begin with frequency selective devices.

COMPONENT CATEGORIES:

- Frequency Selective Devices

3212

FREQUENCY SELECTIVE DEVICES:

1. Filters
    - Low Pass
    - High Pass
    - Band Pass
    - Band Reject (Notch)
2. Multiplexers

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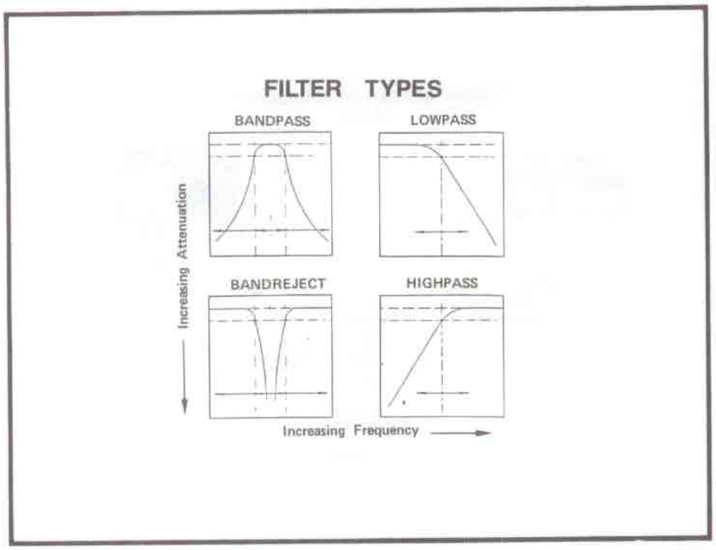
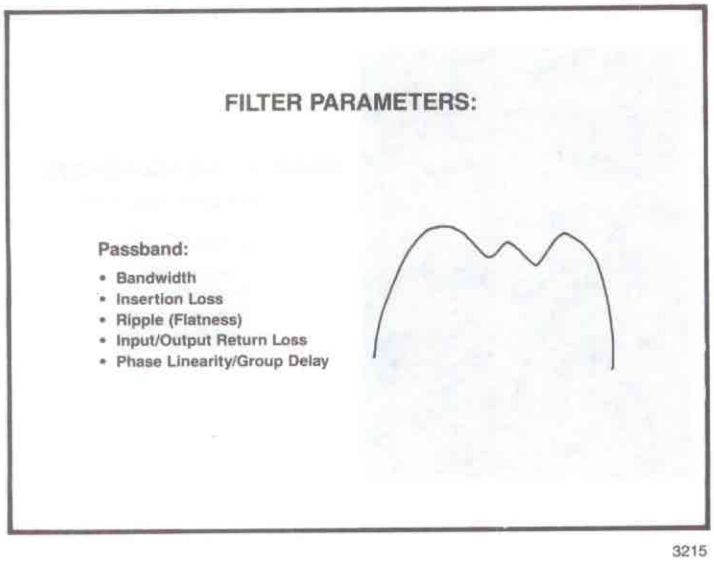
This category includes any device that passes some frequency range and rejects another frequency range. This includes all types of filters and multiplexers. First we will concentrate on filter measurements.



FILTER TYPES

3214

There are four basic filter types as shown here, and each type has certain parameters that characterize it. For example, bandpass filters are often specified by 3-dB bandwidth, and lowpass and highpass filters are specified by upper and lower 3-dB cutoff frequencies.



FILTER PARAMETERS:

Passband:

- Bandwidth
- Insertion Loss
- Ripple (Flatness)
- Input/Output Return Loss
- Phase Linearity/Group Delay

3215

There are a number of parameters commonly specified for filters -- both in the pass band (frequency range that is passed through the filter) and in the stop band (frequency range that is rejected by the filter). The common pass band parameters of importance include bandwidth (or upper/lower cutoff frequency), insertion loss, ripple, return loss, and phase linearity or group delay. The phase component of these parameters will not be considered here.

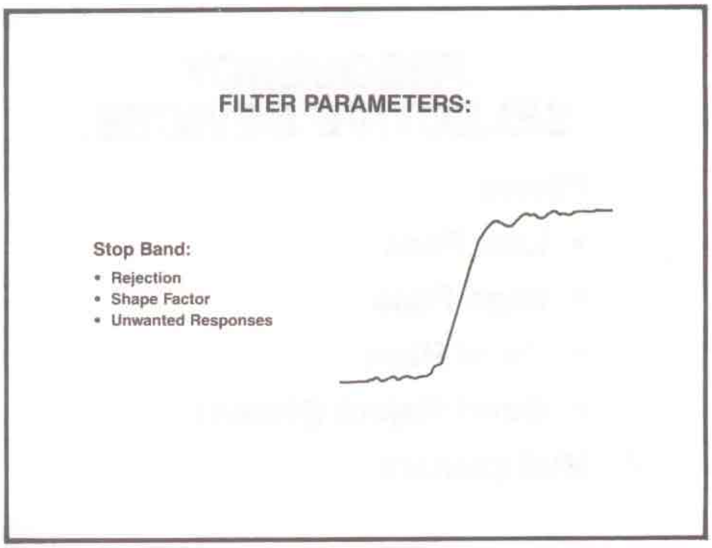
In the stop band, the specifications all relate to how effectively the filter rejects unwanted frequencies, that is, how far down is the response in the stop band from the response in the pass band.

Shape factor, which is defined in several ways, is a quantitative way of describing how quickly the filter makes the transition from the pass band to the stop band. For example, one definition of shape factor on a band-pass filter is as the ratio of the 60 dB bandwidth to the 6 dB bandwidth. If the filter has a shape factor close to 1.0, then it is a very "sharp" filter with steep transition to the stop band.

This slide shows a typical filter measurement with source, directional bridge, detector and analyzer. Note that this setup permits simultaneous measurement of insertion loss, normalized to a "thru" connection, and return loss, normalized to the short/open average. (The HP 8757A and 8756A both guide the user through the short/open calibration procedure, compute the short/open average, and store the average into calibration memory.)

Accurate filter measurements depend on certain characteristics of the measurement system. As discussed earlier, the source and detectors must provide good match to avoid re-reflections that cause mismatch errors, particularly for measurements in the pass band (low insertion loss). The measurement of the stop band response requires a wide dynamic range and low source harmonics.

Let's take a look at a 3-5 GHz band-pass filter. We will characterize the insertion loss, bandwidth, passband ripple, and return loss.

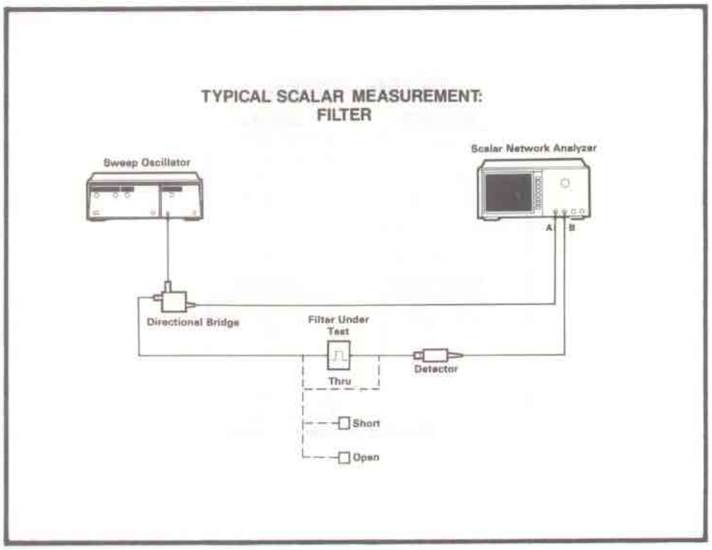


FILTER PARAMETERS:

Stop Band:

- Rejection
- Shape Factor
- Unwanted Responses

3216



TYPICAL SCALAR MEASUREMENT:
FILTER

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EXAMPLE MEASUREMENT:

3-5 GHz Band Pass Filter

TO MEASURE:

- Insertion Loss
- Bandwidth
- Pass Band Ripple
- Input Return Loss

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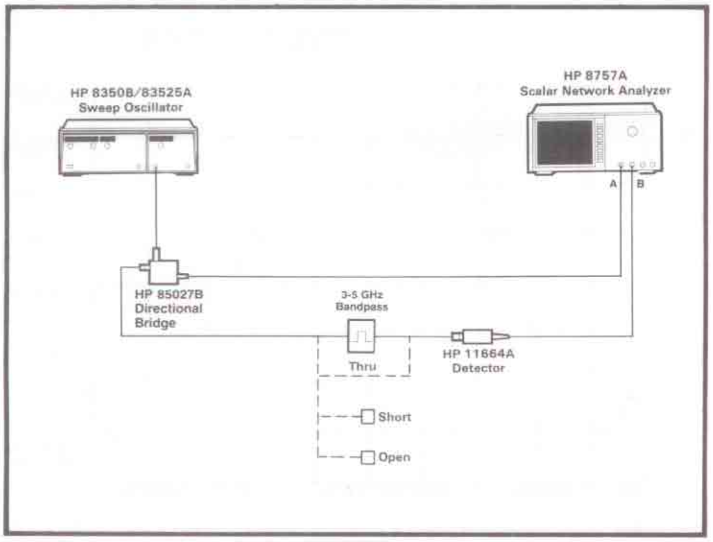

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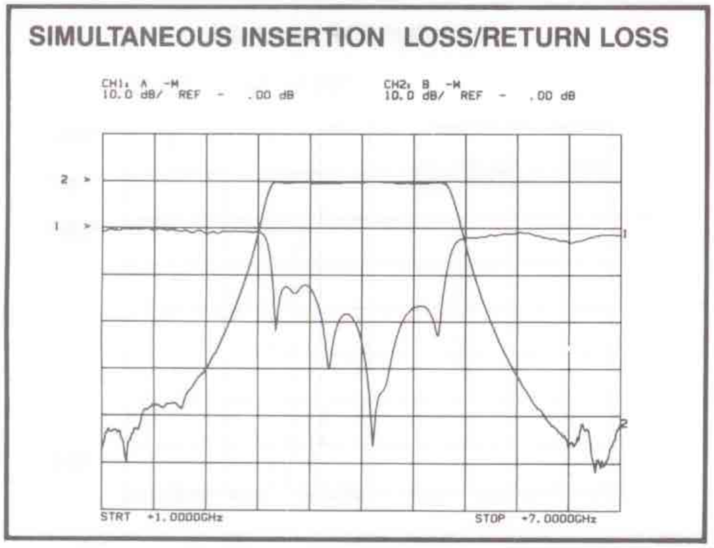
Here is the measurement hardware used. Remember that the directional bridge introduces a 6-dB power loss, which will decrease the dynamic range of the measurement by 6 dB. If the dynamic range were needed, a directional coupler could be used instead of a bridge.



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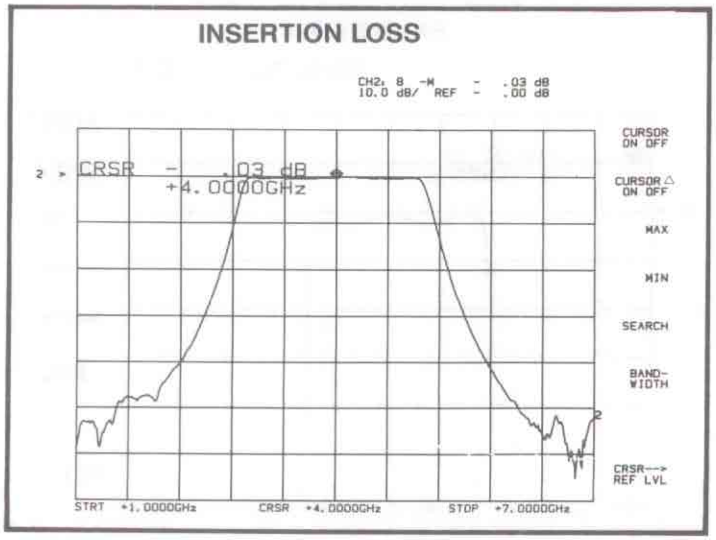
Shown here are insertion loss and return loss responses. Both are normalized to the appropriate calibration standards, as indicated by the "measurement minus memory" labels "A - M" and "B - M". The short/open average is stored in channel 1 memory, and the "thru" is stored in channel 2 memory.



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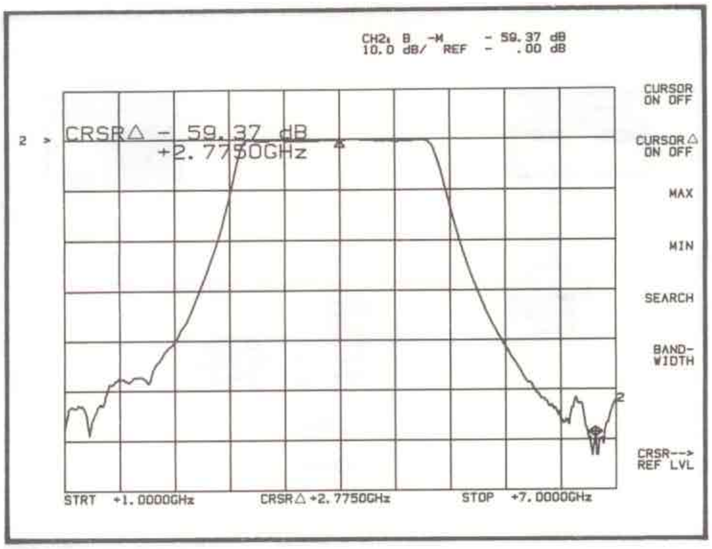
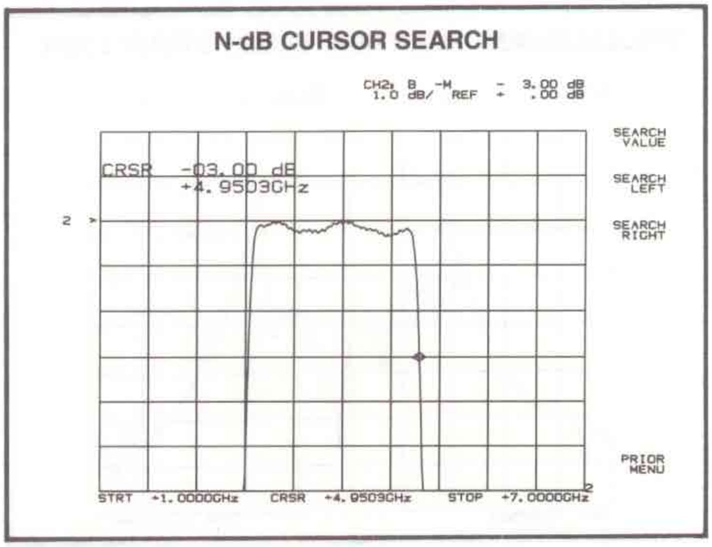
Now let's take a closer look at the insertion loss data. Using a "cursor", the operator can dial a pointer to any point on the trace for a quick, clear reading of the measured insertion loss and the frequency. With "cursor max" and "cursor min", the cursor moves to the highest or lowest point on the trace.

For a quick reading of the relative relationship between two data points (magnitude and frequency difference), the cursor delta function is available. For example, if we want to measure the out-of-band response relative to the pass band, we would dial the cursor to the reference point in the pass band and activate the cursor delta. A marker is placed at that data point, and the cursor can be moved into the stop band. The analyzer display now shows the difference -- both magnitude and frequency -- between that point and the fixed reference marker. In this case we measure 59 dB of rejection 2.775 GHz from the center frequency.



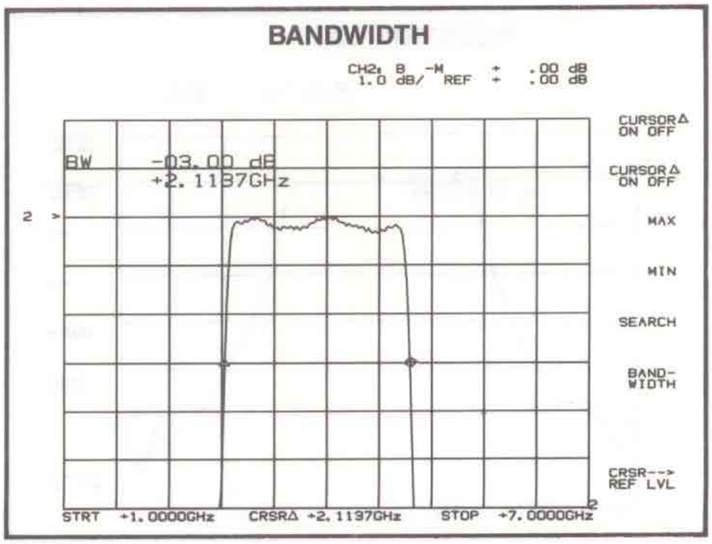
3223

We can also locate the frequencies where the response is down by some exact amount, for example 3 dB. This point can be found using the cursor delta or by using the "N dB search" function of the HP 8757A. The operator can quickly search for the left hand 3-dB point (search left) or the right hand 3-dB point (search right). The 3-dB points of this filter are 2.84 GHz and 4.95 GHz.


N-dB CURSOR SEARCH

3224

To measure the bandwidth, or the difference between the two 3-dB points, cursor delta can again be used. Or to avoid dialing in to the 3 dB points, the "bandwidth" function of the HP 8757A will perform the searches automatically and display the difference between the two 3-dB points, that is, the bandwidth. In this case, the bandwidth is 2.1137 GHz.


BANDWIDTH

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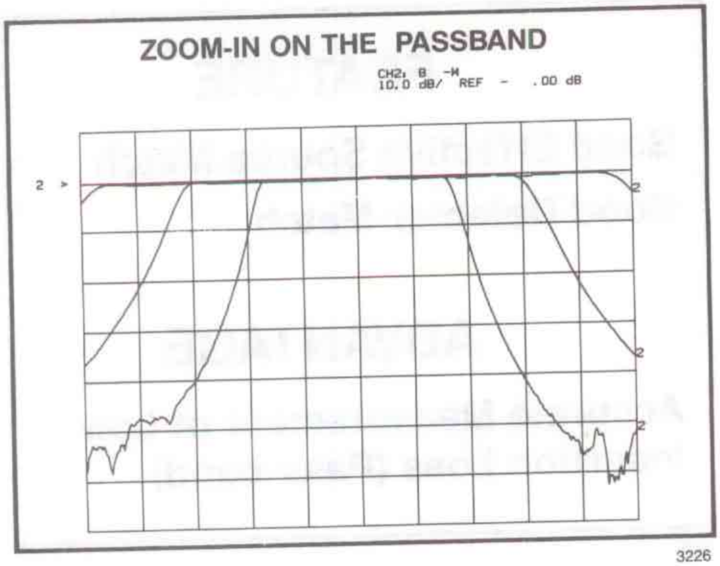
The data in these measurements is digitized at discrete frequencies. In general, no digitized data point will be exactly 3.00 dB. Therefore, both the search and bandwidth features use linear interpolation between data points to find the exact 3.00 dB points.



ZOOM-IN ON THE PASSBAND

3226

Now let's zoom in on the passband and look at the passband ripple more closely. This is easily accomplished by narrowing the swept frequency range on the source, delta F. When this is done, the HP 8757A adjusts the calibration data to retain calibration.

FEATURE

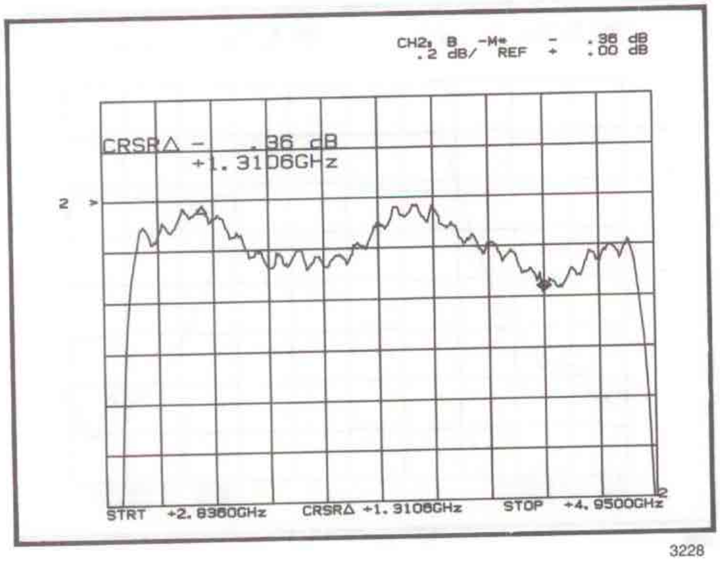
Adaptive Calibration

ADVANTAGE

Allows You to Narrow the Frequency Span and Retain Calibration

3227

This "adaptive calibration" feature makes measurements more convenient, because it is not necessary to recalibrate when the frequency span is narrowed.



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The passband ripple can now be observed with high resolution, in this case 0.2 dB per division. The cursor delta function again shows the variation in response, in this case a 0.36 dB peak to peak ripple. It is important to remember that some of this ripple could be caused not by the filter but by the measurement system itself. The extent of this measurement system ripple, as you may recall from the fundamentals section, depends on the impedance match of the detector and of the source. With good source and detector match, these measurement system responses can be kept to a minimum.

Remember good effective source match and good detector match are particularly important when measuring devices with low insertion loss, since reflected signals pass through the device under test with little or no attenuation. Therefore, detector and source match are important in measurements of insertion loss in the pass band.

FEATURE

Good Effective Source Match

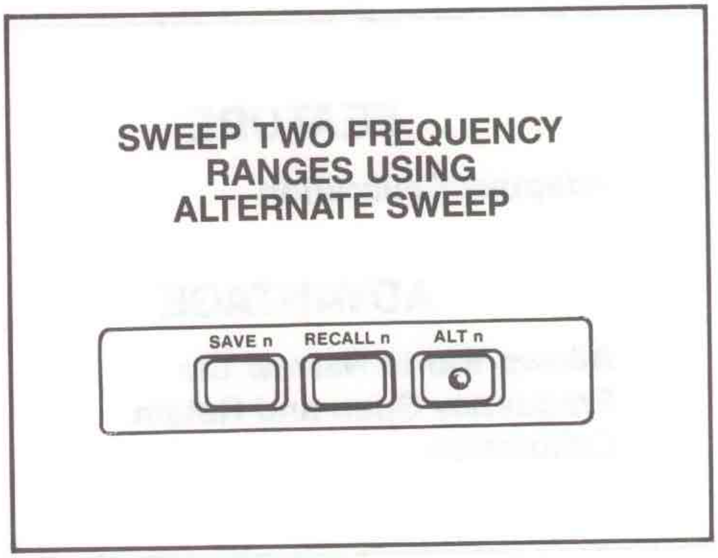
Good Detector Match

ADVANTAGE

Accurate Measurement of Low Insertion Loss (Pass band)

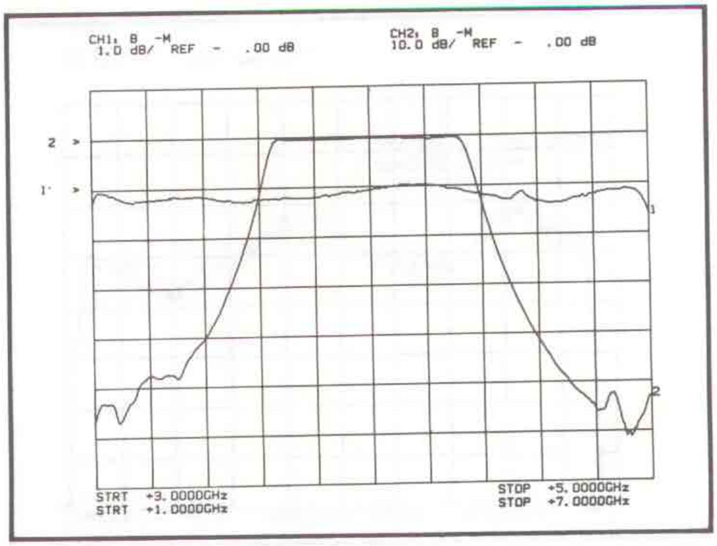
3229

When measuring filters it is often useful to view two different frequency ranges simultaneously. This can be accomplished using the ALTERNATE SWEEP function of HP swept sources.



3231

Using ALTERNATE SWEEP, we can view the passband response (2 GHz sweep) and the wideband response (6 GHz sweep) at the same time. Both traces are "live" and will respond to device adjustments in real time. Tradeoffs between passband ripple and the slope of the filter skirts can be analyzed as adjustments are made.



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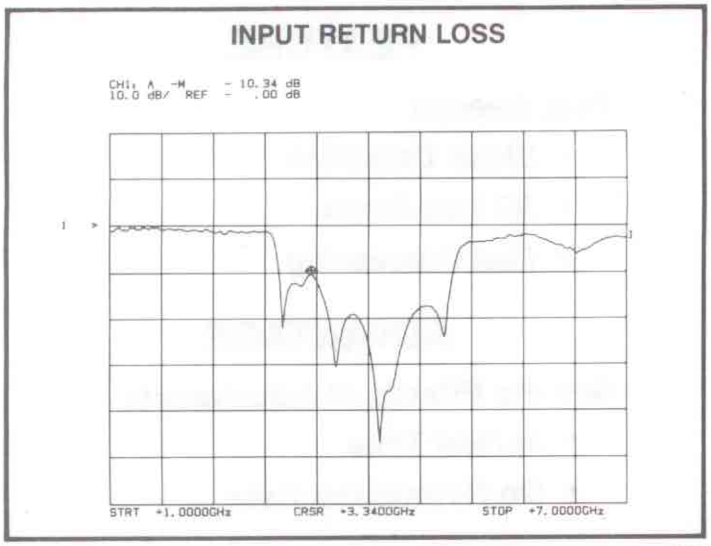

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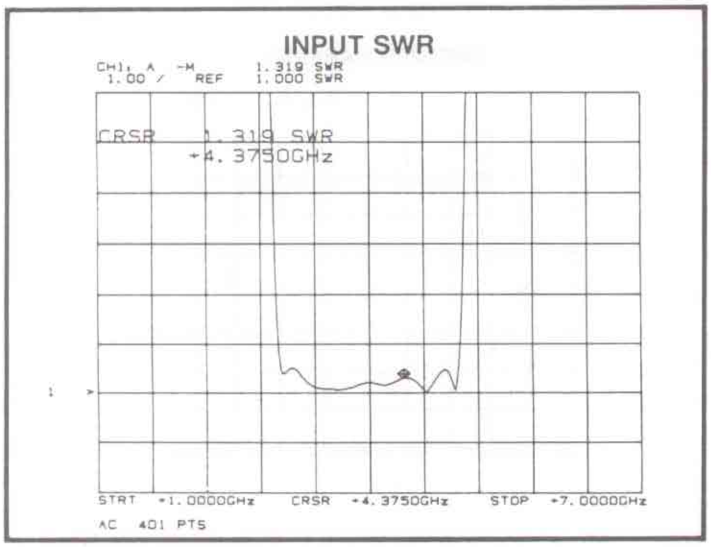
This plot shows input return loss of the filter. The example filter exhibits high return loss in the passband (20 dB), indicating good impedance match.

When making reflection measurements of low loss devices, it is sometimes necessary to terminate the output of the device with a 50 ohm load, instead of using the detector as the termination. This reduces error by reducing re-reflections.



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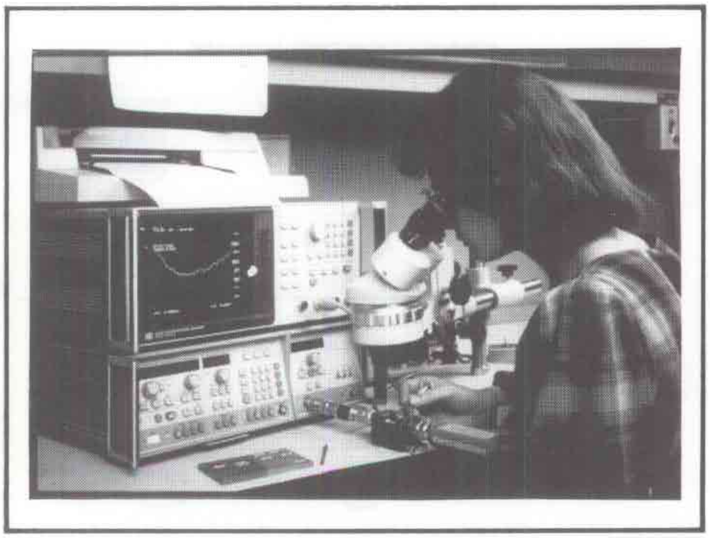
With the HP 8757A, it is also possible to display the reflection trace in standing wave ratio.



3406

Filters and other devices are often adjusted using the scalar analyzer's display of insertion loss or return loss as a guide. When making these adjustments it is often necessary to see the effects of the adjustments appear on the display "in real time" so that the operator can relate what the hand is doing with what the eye is seeing. It is therefore important to have fast sweeps so that the data is updated quickly.

As discussed in the fundamentals section, diode detection and AC log amplifiers are very fast at all power levels. With digital analyzers such as the HP 8757A and 8756A, the sweep time is not limited by the detectors or by the log amplifiers, but only by the analyzer's speed in digitizing and processing the data.

Fast sweeps allow the operator to see the effects of adjustments in real time and on normalized data. The HP 8757A allows the user to trade off resolution and sweep time. For example, 50 ms sweep at 101 data points.

FEATURE

Fast Sweeps
- Diode Detection
- AC Log Amps
- Fast Processing

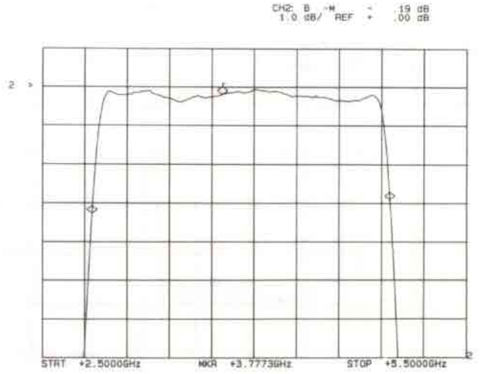
ADVANTAGE

See the Effects of Adjustments
- In Real Time
- On Normalized Data

3236

To get a readout of frequency, the operator has several choices. As we have already mentioned, the analyzer's cursor provides a quick reading of both magnitude and frequency. In addition, up to five sweeper markers are also available from HP sweep oscillators, and like the cursor, they can be dialed to any data point and both magnitude and frequency can be read.

SWEEPER MARKERS



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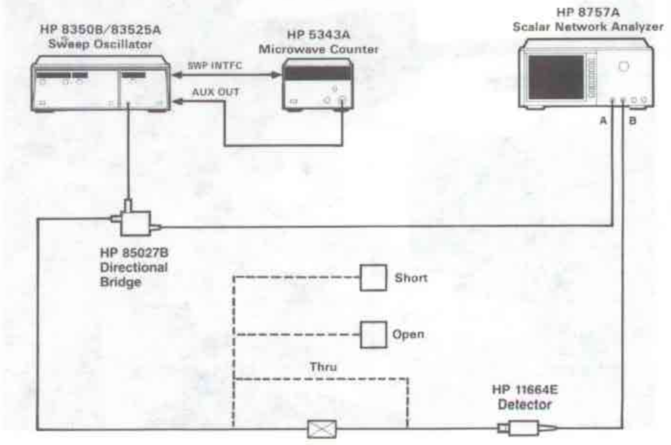
In many filter applications it is necessary to make highly accurate measurements of marker frequencies, for example for 3-dB points. Using the HP 5343A microwave counter, sweeper markers can be counted precisely. A highly stable time base and a sweep oscillator interface allow the HP 5343A to make high resolution measurements of marker frequency.

COUNTING SWEEPER MARKERS



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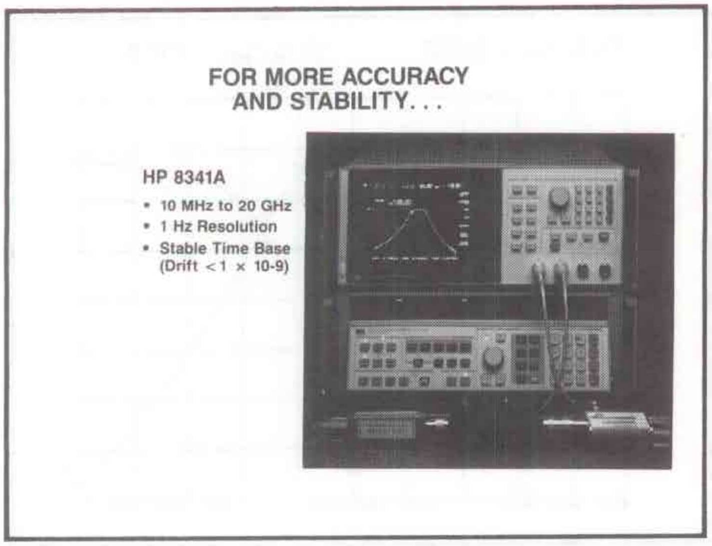


FOR MORE ACCURACY AND STABILITY. . .

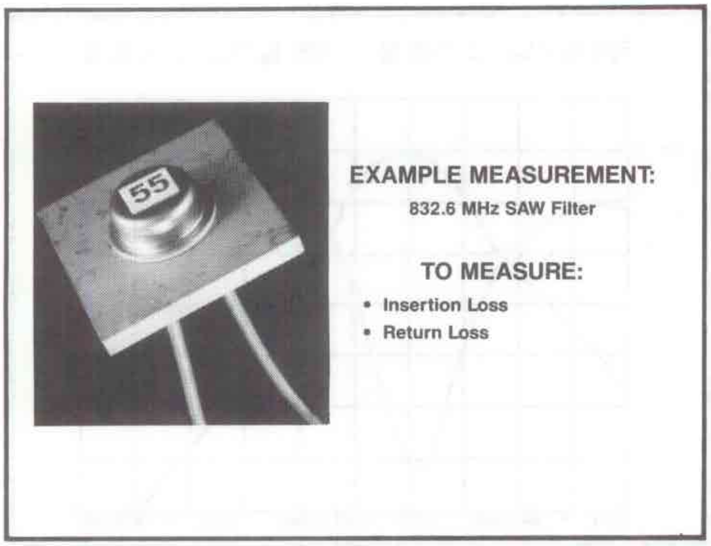
HP 8341A

- 10 MHz to 20 GHz
- 1 Hz Resolution
- Stable Time Base (Drift < 1 × 10-9)

3242

Some applications demand more frequency accuracy and stability than the HP 8350B can offer even with counted markers. One example is the measurement of a filter with a very narrow bandwidth. A synthesized sweeper is ideal for these applications.

The HP 8341A synthesized sweeper, for example, provides 10 MHz to 20 GHz frequency coverage with high resolution and stability. Let's look at an example application of a synthesized sweeper.



EXAMPLE MEASUREMENT:

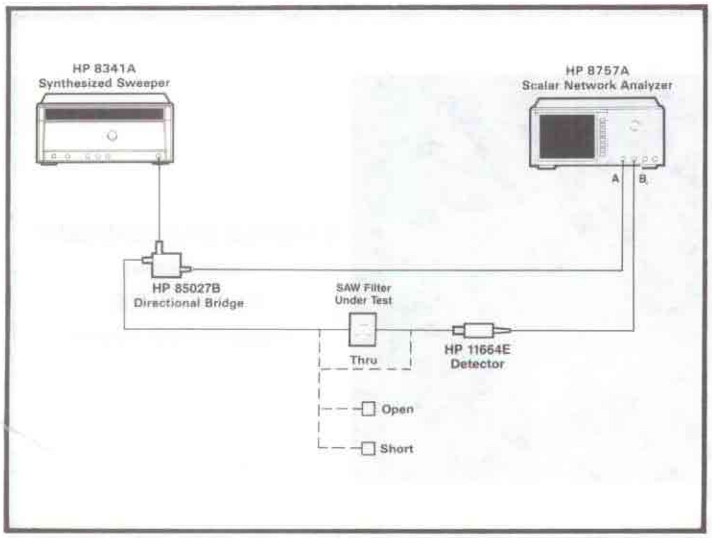
832.6 MHz SAW Filter

TO MEASURE:

- Insertion Loss
- Return Loss

3243

The next example filter is a surface acoustic wave (SAW) filter with very narrow bandwidth. We will perform a simultaneous measurement of insertion loss and return loss, and see why a synthesized sweeper is required in this application.



HP 8341A Synthesized Sweeper

HP 8757A Scalar Network Analyzer

HP 85027B Directional Bridge

SAW Filter Under Test

Thru

HP 11664E Detector

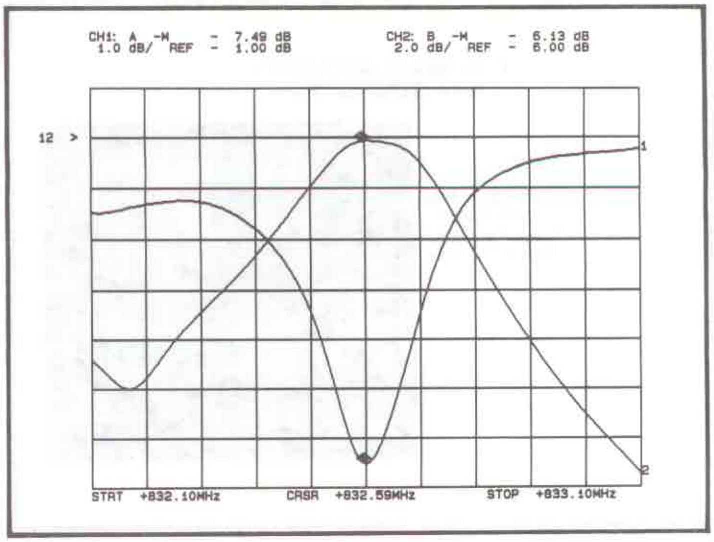
Open

Short

3244

Except for the source and the frequency range, this measurement setup is identical to the one used for the 3-5 GHz bandpass filter.

This plot shows the device characteristics. Note that the frequency span is only 1 MHz. What would happen if we tried to make this measurement with the HP 8350B sweep oscillator?



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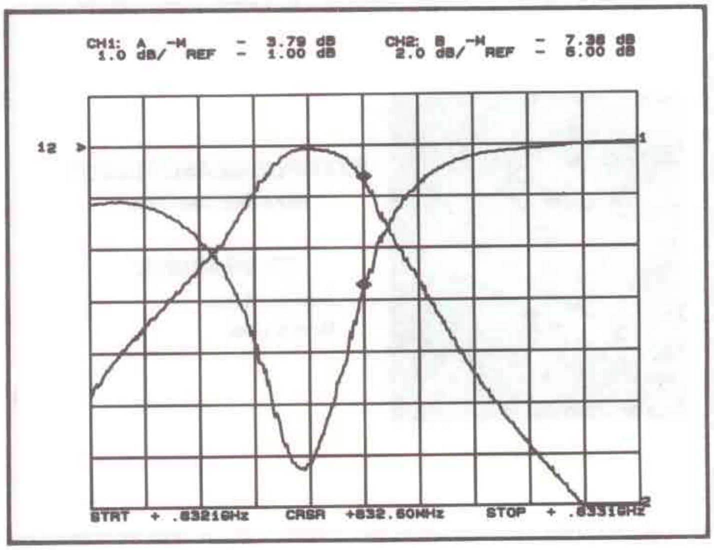
This plot shows the same measurement with the HP 8350B as the source. Notice that the center frequency is offset slightly, and that the trace is distorted by the variations in the source frequency (residual FM) as the measurement is made. This narrowband device requires the frequency accuracy and stability of the synthesized sweeper.



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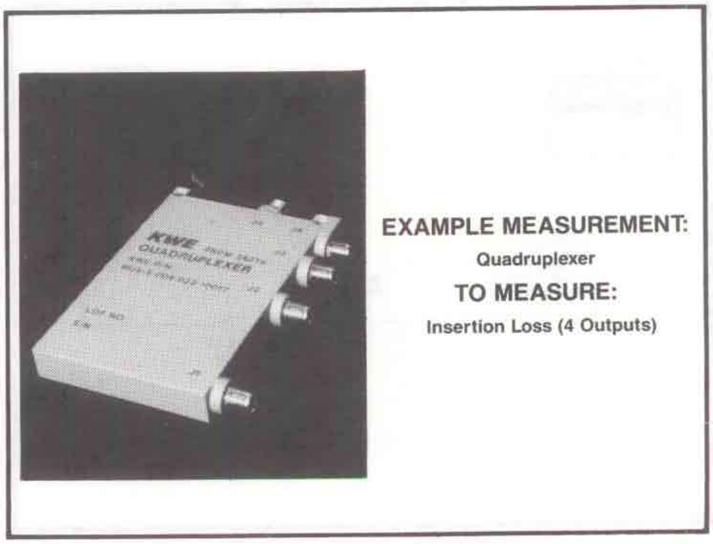
At the start of this section we mentioned multiplexer measurements. A multiplexer is a combination of filters which allows a different frequency range to pass to each of several output ports. Here is a quadruplexer (4 output ports) that can be easily characterized with scalar network measurements.



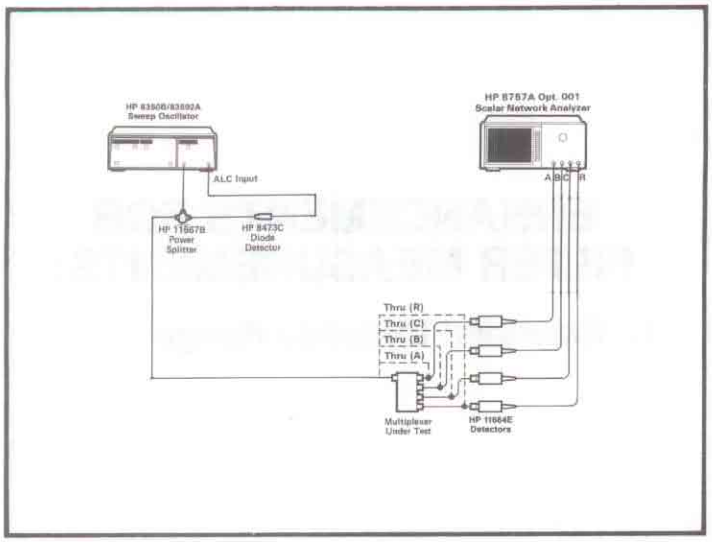
EXAMPLE MEASUREMENT:

Quadruplexer

TO MEASURE:

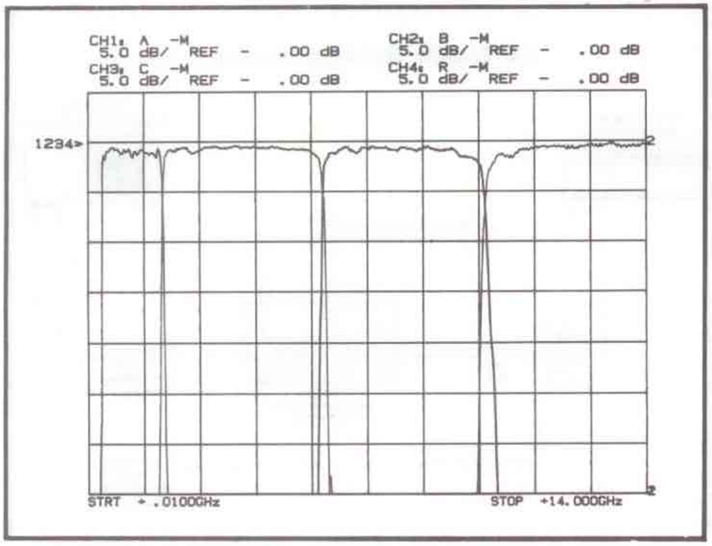
Insertion Loss (4 Outputs)

3252



3253

Using this test setup, and the HP 8757A option 001 (fourth detector input), we can measure the insertion loss of all four inputs simultaneously. Note that a separate "thru" calibration must be done for each detector. Improved source match is achieved using external source leveling.



3254

This plot shows the response at all four quadruplexer outputs simultaneously. The cursor search and bandwidth functions can be used separately for each channel and real time adjustments can be made.

FEATURE

Four Detector Inputs

(HP 8757A Opt. 001)

Four Independent Display Channels

ADVANTAGE

View Insertion Loss of All Four Channels in Real Time

3255

Four detector inputs and four display channels make this measurement very convenient.

Some filter measurement applications require enhancements to the measurement system. For example some measurements demand more dynamic range than the standard scalar analyzer provides.

ENHANCEMENTS FOR FILTER MEASUREMENTS:

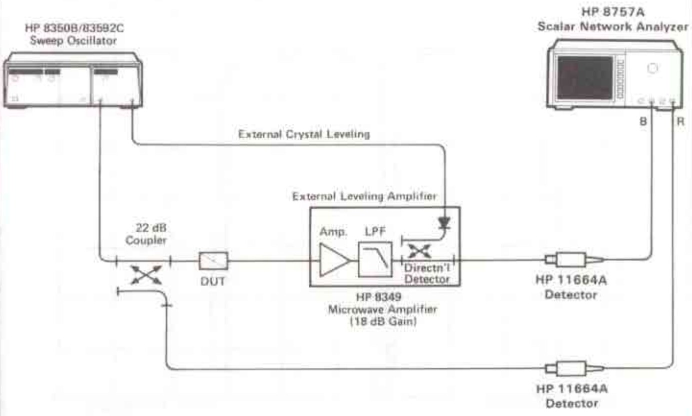
1. Extended Dynamic Range

3256

Using an amplifier, it is possible to extend the effective dynamic range of a measurement. In the normal configuration without any amplifier, the dynamic range is limited to the dynamic range of one detector, for example only the B detector in a transmission measurement. Using a source with a good leveling range and an amplifier and external source leveling, it is possible to increase the dynamic range by combining the ranges of two detectors in a ratio measurement.

This extended dynamic range measurement is described in detail in HP application note 327-1.

EXTENDED DYNAMIC RANGE



3257

The amount of dynamic range achieved using this method is summed up in this equation. The minimum dynamic range realized is Po-Sa+Ga, where Po is the maximum unleveled power available from the source (+8 dBm for HP 83592C), Sa is the minimum sensitivity of the B detector (-60 dBm for the HP 11664A and the HP 8757A), and Ga is the gain of the amplifier (+18 dB for the HP 8349A). This equation yields at least 86 dB of dynamic range for the HP 83592C, HP 11664A, and the HP 8349A.

MINIMUM DYNAMIC RANGE

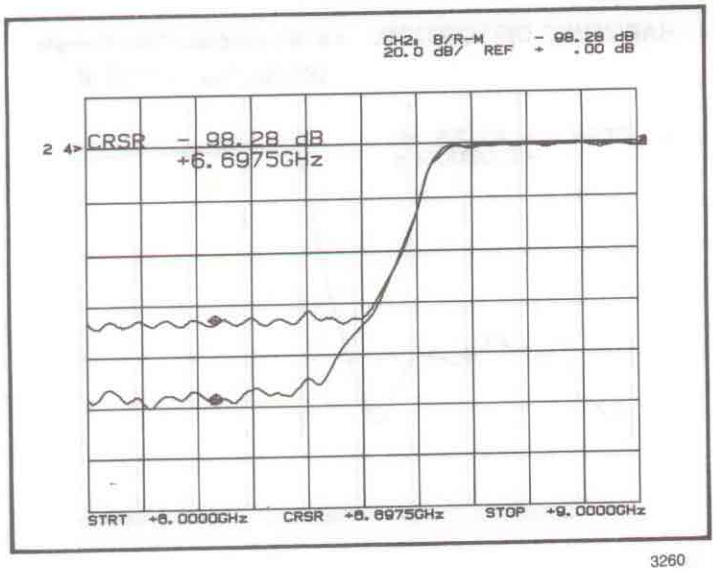
$$= P_o - S_a + G_a$$

Where P_o = Maximum Power of Source

S_a = Sensitivity of Detector

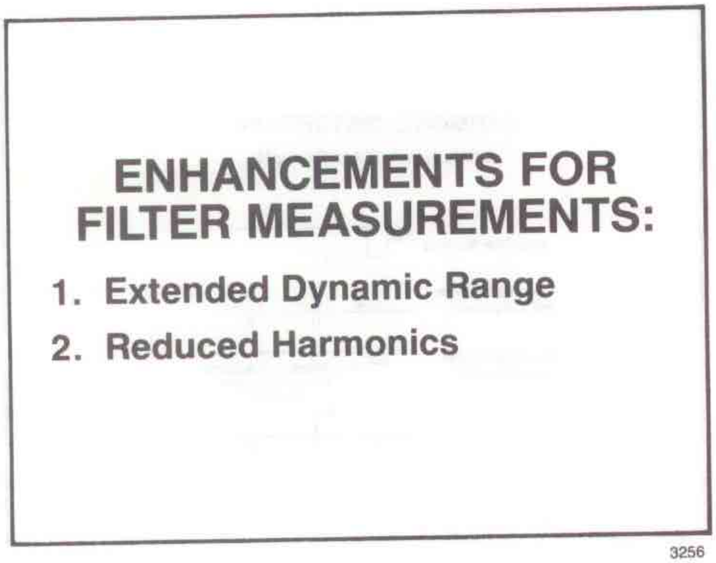
G_a = Gain of Amplifier

3259



3260

Here is an example of an extended dynamic range measurement of an 8-10 GHz bandpass filter. In this example we realize over 95 dB of effective dynamic range.

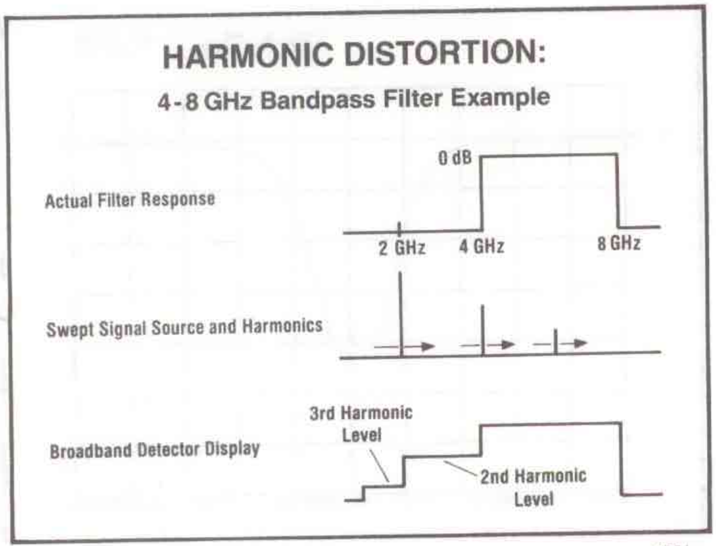


ENHANCEMENTS FOR FILTER MEASUREMENTS:

1. Extended Dynamic Range
2. Reduced Harmonics

3256

Another way to enhance filter measurements is to reduce the distortion due to the harmonics of the source. Before we discuss reduced harmonics, let's talk briefly about how harmonic distortion can affect a filter measurement.



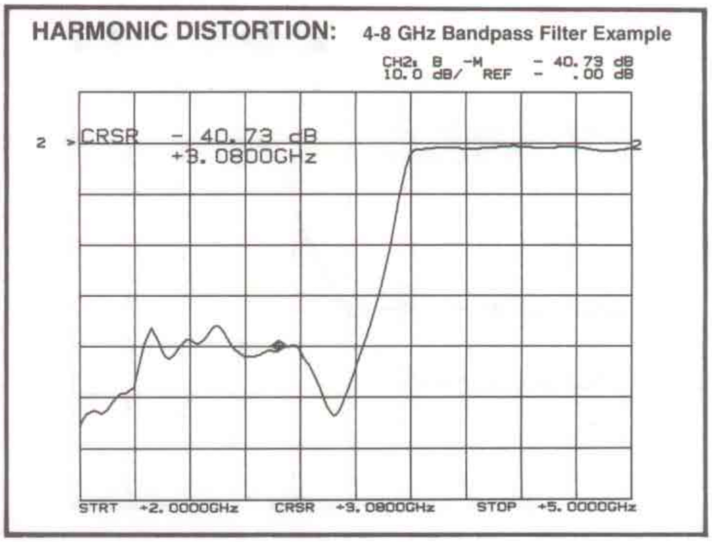
HARMONIC DISTORTION:

4-8 GHz Bandpass Filter Example

3261

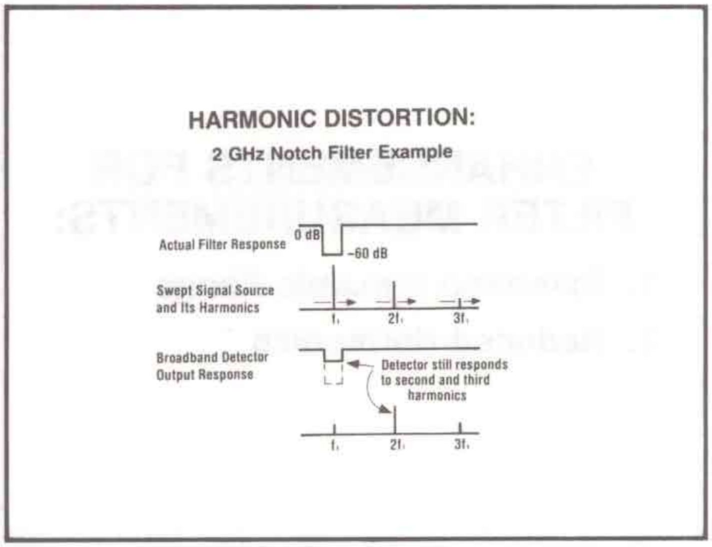
In this example measurement of a 4-8 GHz bandpass filter, source harmonics cause a "staircase" response that is not the true filter response. This distortion is caused by the harmonics of the source which pass through the filter passband before the fundamental.

This plot shows this staircase on a 4-8 GHz bandpass filter.


HARMONIC DISTORTION: 4-8 GHz Bandpass Filter Example

3262

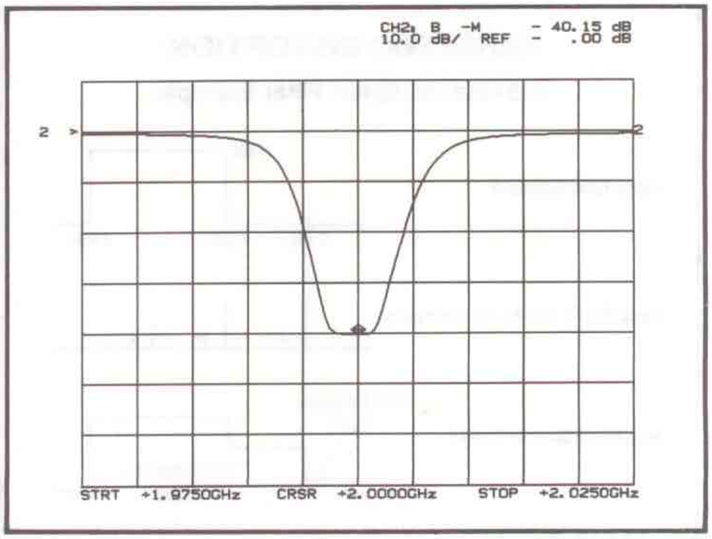
Another example shown here is a 2 GHz band-reject or notch filter. Since the harmonics are passed through the filter as the fundamental is in the reject band, the harmonics tend to fill in the notch, and distort the measurement of the true filter response.


HARMONIC DISTORTION:

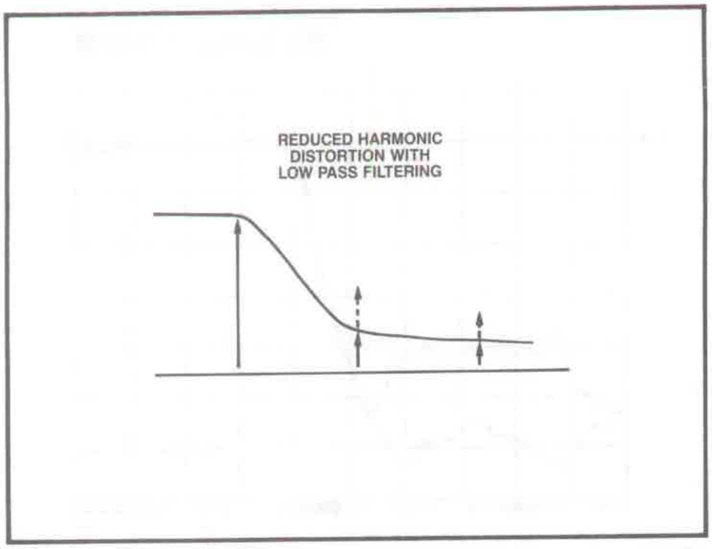
2 GHz Notch Filter Example

3263

Here is an actual plot of a 2 GHz notch filter. Although the filter's actual rejection is over 50 dB in the notch, this measurement shows only 40 dB.



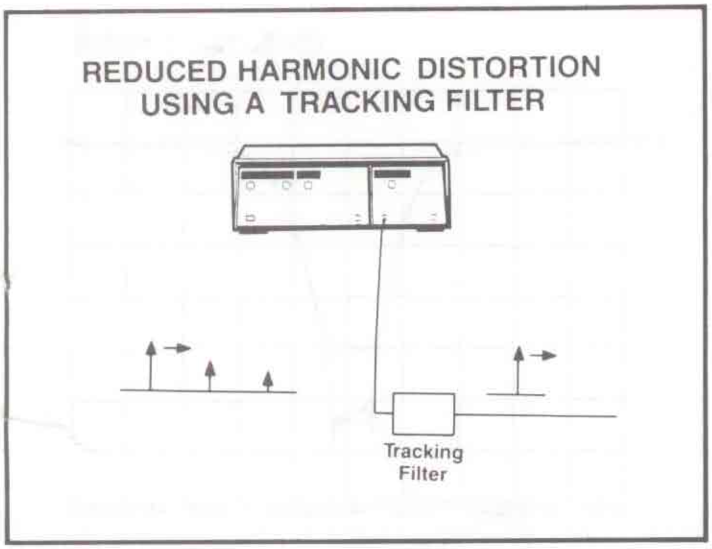
3264



REDUCED HARMONIC DISTORTION WITH LOW PASS FILTERING

3265

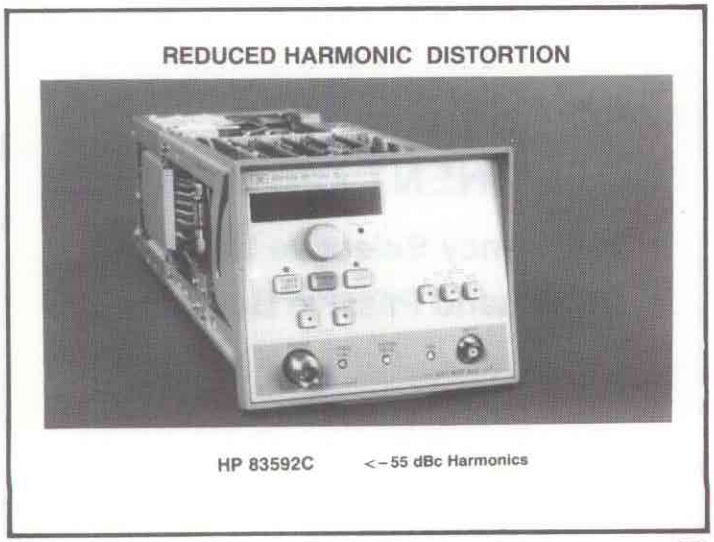
There are several ways to reduce harmonic distortion. The first is simply to filter out the harmonics using a lowpass filter with a cutoff frequency that reduces the harmonics but does not affect the full sweep range of the fundamental. This method is often inconvenient for broad filters, such as the 4-8 GHz bandpass filter, because several filters would be necessary to cover the frequency range in steps. However lowpass filtering is a simple way to reduce harmonic distortion in many applications.



REDUCED HARMONIC DISTORTION USING A TRACKING FILTER

3267

A tracking filter can also be used to reduce harmonic distortion even over broad sweeps. This setup shows an example configuration using a tracking filter to provide <-55dBc harmonics.



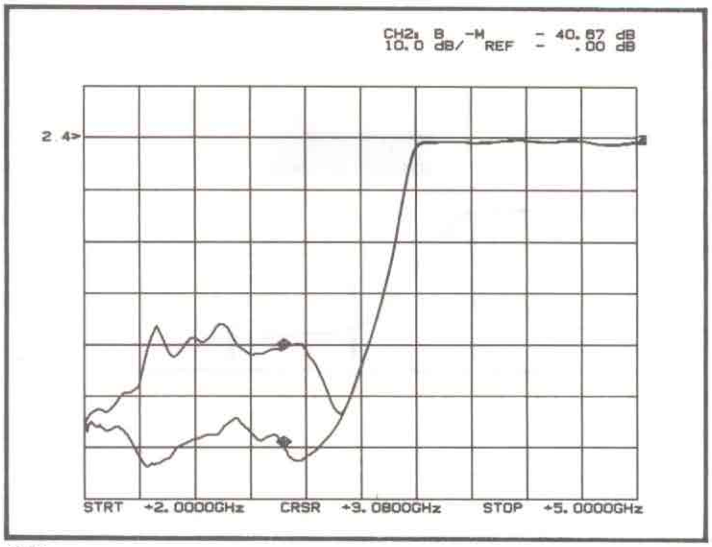
REDUCED HARMONIC DISTORTION

HP 83592C <−55 dBc Harmonics

3266

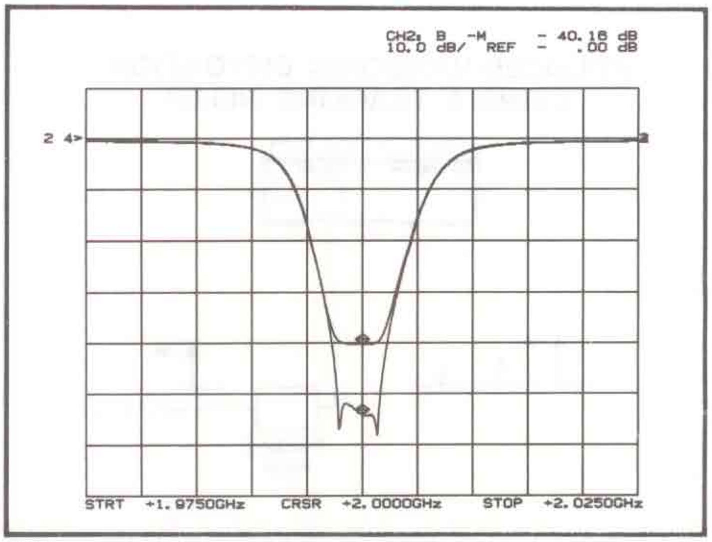
Another way to reduce harmonic distortion is to use a source with lower harmonic content. The HP 83592C plug-in for the HP 8350B sweep oscillator uses an internal tracking filter to provide <-55 dBc harmonics from 3.5 GHz to 20 GHz.

When harmonic distortion is reduced, the true filter response can be seen. This plot shows the measurement of the 4-8 GHz bandpass filter made with the HP 83592C. Notice that the staircase response is greatly reduced.



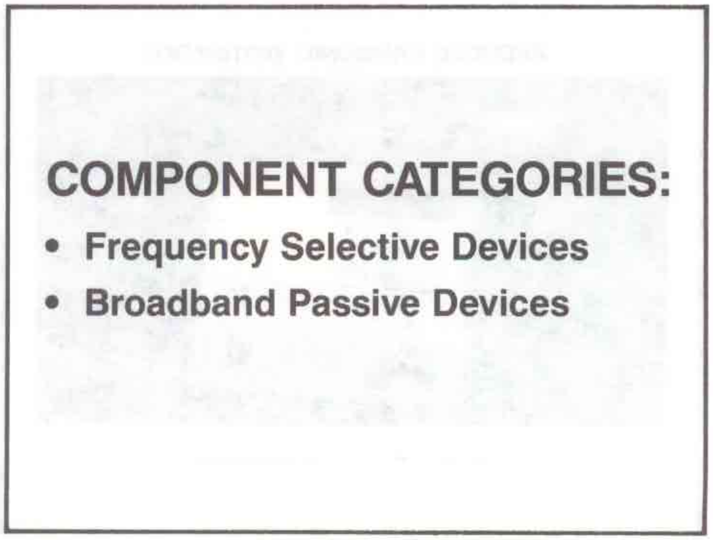
3268

This plot shows the notch filter measurement with the harmonic distortion removed. Notice that it is possible to see much farther into the notch.



3269

The next component category is broadband passive devices. These devices usually operate over a very broad frequency range and exhibit only small variations in response over that broad frequency range.



COMPONENT CATEGORIES:

- Frequency Selective Devices
- Broadband Passive Devices

3270

BROADBAND PASSIVE DEVICES:

- Transmission Lines
- Resistive Networks
- Terminations
- Isolators
- Attenuators
- Switches

3271

Transmission lines, resistive networks, terminations, isolators, attenuators, and switches are all examples of broadband passive devices.

BROADBAND PASSIVE DEVICE PARAMETERS:

- Insertion Loss
- Return Loss (SWR)
- Phase Linearity/Group Delay
- Phase Tracking

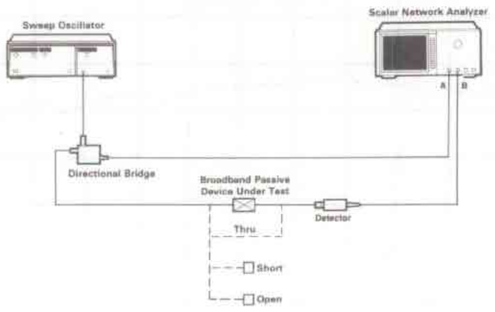
3272

The parameters important to measure on broadband passive devices include insertion loss, return loss, phase linearity, and phase tracking. Again we will restrict ourselves to magnitude only (scalar) measurements.

A typical reflection/transmission measurement of a broadband passive device is shown here. This is very similar to the filter measurement setup.

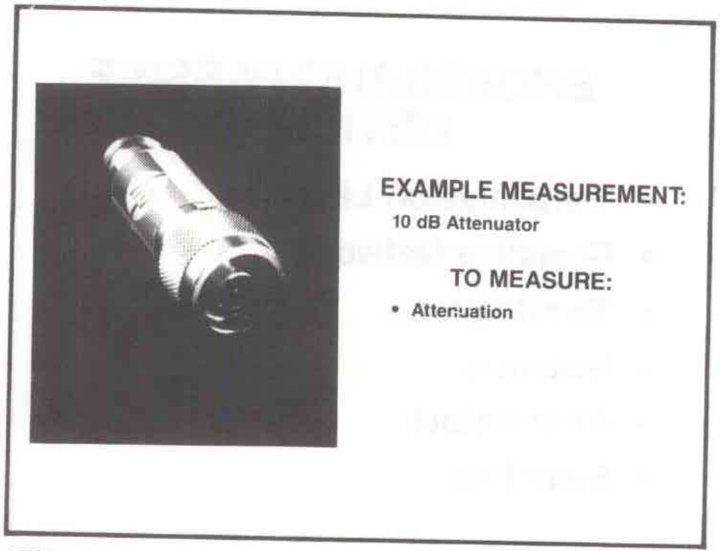
The measurement system necessary to characterize broadband passive devices must meet certain requirements. Wide frequency coverage (e.g., 10 MHz to 26 GHz) is often required. Because many broadband devices have low insertion loss, it is important to have good source and detector match to avoid the effects of re-reflections. Broadband devices also often have high return loss, so high directivity is important for accurate measurments. Switches and some attenuators require that the measurement system have a very wide dynamic range. Other parameters, such as low harmonics and high frequency accuracy are not usually required for measuring broadband passive devices.

TYPICAL SCALAR MEASUREMENT: BROADBAND PASSIVE



3273

The first example broadband passive device is a 10 dB attenuator. Attenuators such as this one are often used in preliminary measurements to verify the performance of the measurement system.



EXAMPLE MEASUREMENT:

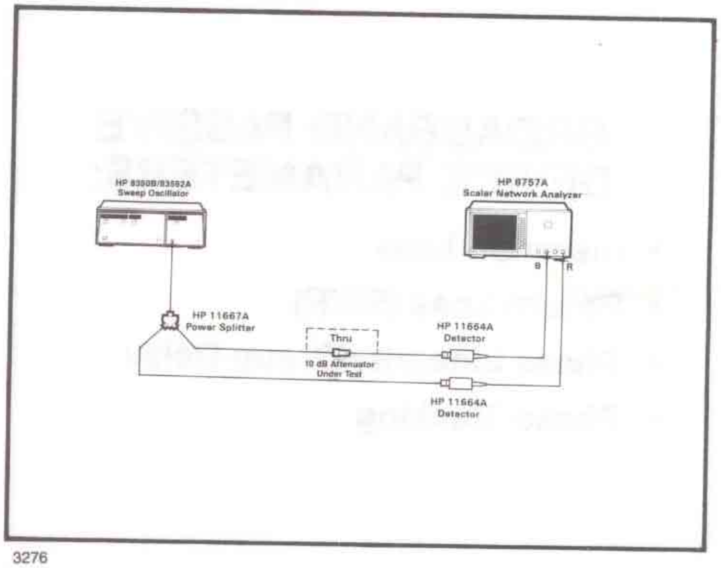
10 dB Attenuator

TO MEASURE:

- Attenuation

3276

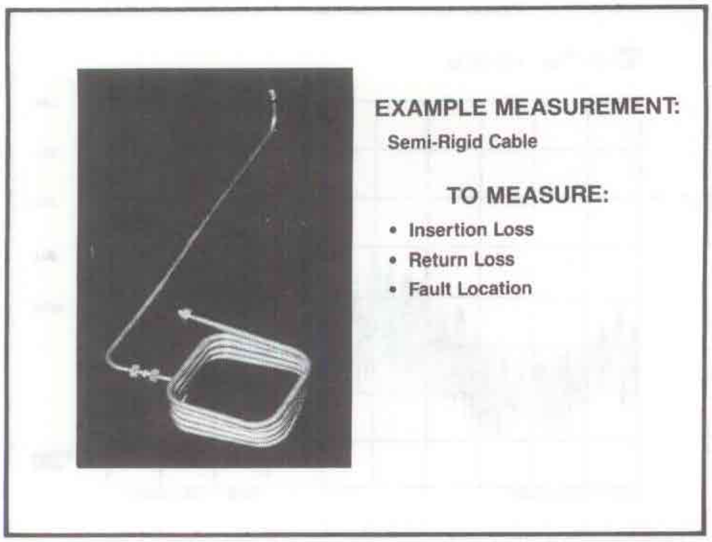
This setup will provide a ratio measurement of insertion loss data from 10 MHz to 18 GHz. Remember that ratioing improves the effective source match by removing the effects of source power variations versus frequency. Note, however, that it is still necessary to perform the "thru" calibration to remove the effects of any differences in frequency response (tracking) between the two arms of the power splitter and between the two detectors.



3276

This plot shows the normalized and ratioed frequency response (B/R-M). Note that the response variation is small over the entire frequency range.

3277



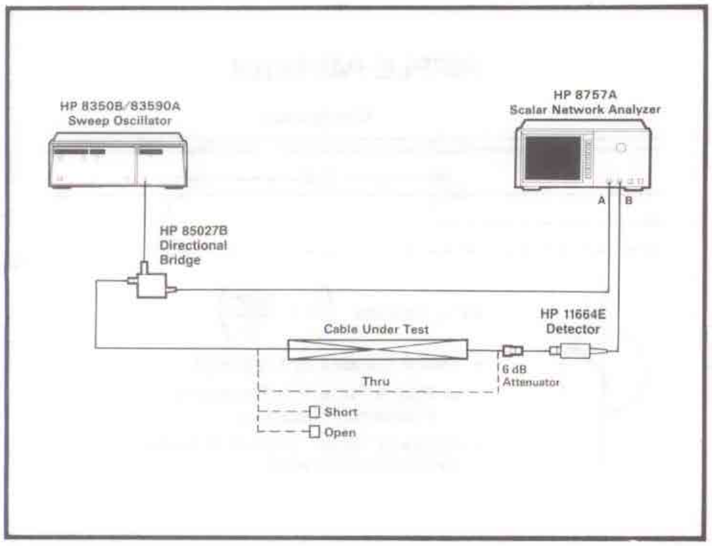
EXAMPLE MEASUREMENT:
Semi-Rigid Cable

TO MEASURE:

- Insertion Loss
- Return Loss
- Fault Location

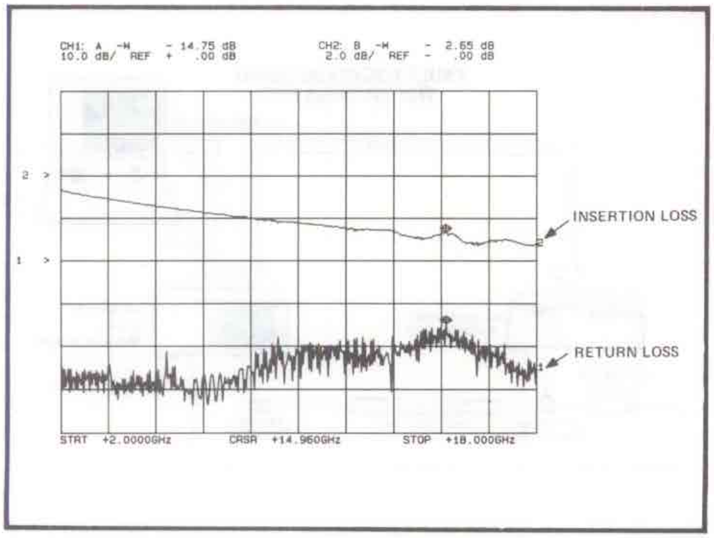
3280

The next example measurement of broadband passive devices is two sections of semi-rigid cable (RG-141) connected together. We will show the measurements of insertion loss and return loss and also show how fault location can be used to locate impedance mismatches along the line.



3281

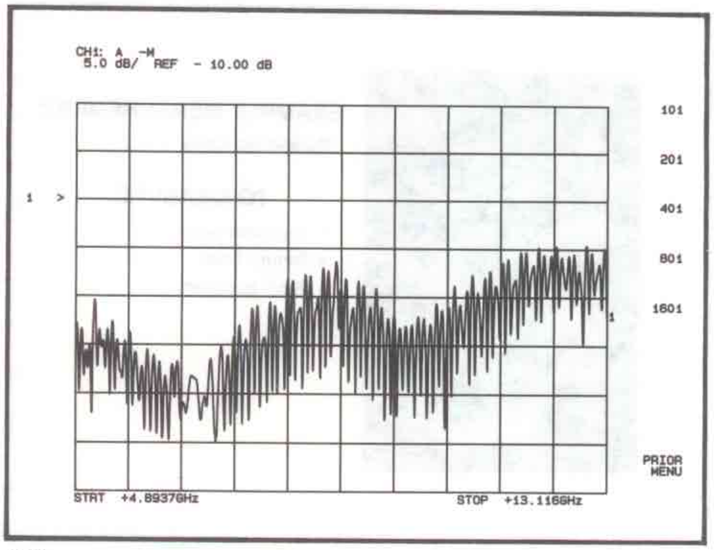
This setup is used to measure insertion loss and return loss simultaneously over a broad frequency range of 2-18 GHz. A 6 dB attenuator is used to isolate the detector and reduce the effects of re-reflections. (Effective detector match, remember, is particularly important when measuring low insertion loss devices.) The familiar thru and short/open calibrations are performed.



3282

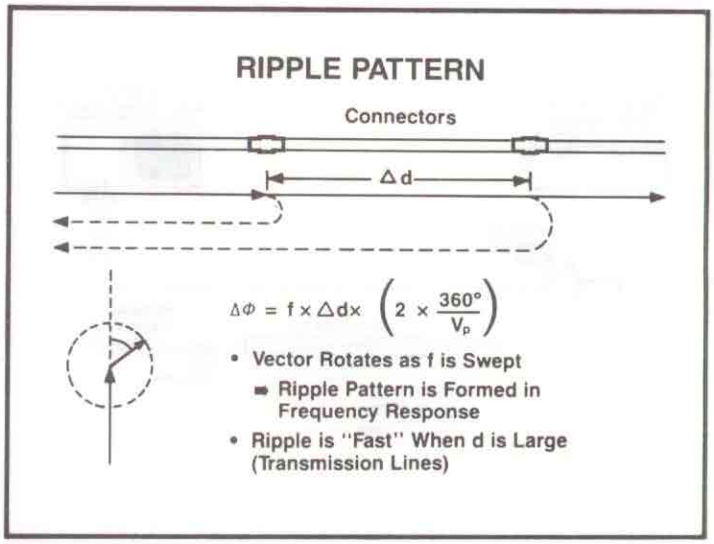
The resulting data is shown here. Note that the insertion loss is low, as it should be for any transmission line. Also note that return loss is high (near 25 dB), so high directivity is required to make this measurement accurately. The fast variation in the return loss plot is typical of many transmission line measurements and is worth some consideration.

This plot shows return loss over a narrower frequency span with 1601 point resolution. Note that the ripples are well-characterized. Let's discuss briefly the origin of this ripple.



3283

Signals reflected from various points within the line will combine vectorially to form the detected reflection response. When a signal travels down a line, it undergoes a phase shift that is proportional to both frequency and distance. In a long line (d large), the phase shift between signals reflected from various points in the line will vary rapidly with frequency. The result is the rapid ripple in the frequency response trace.



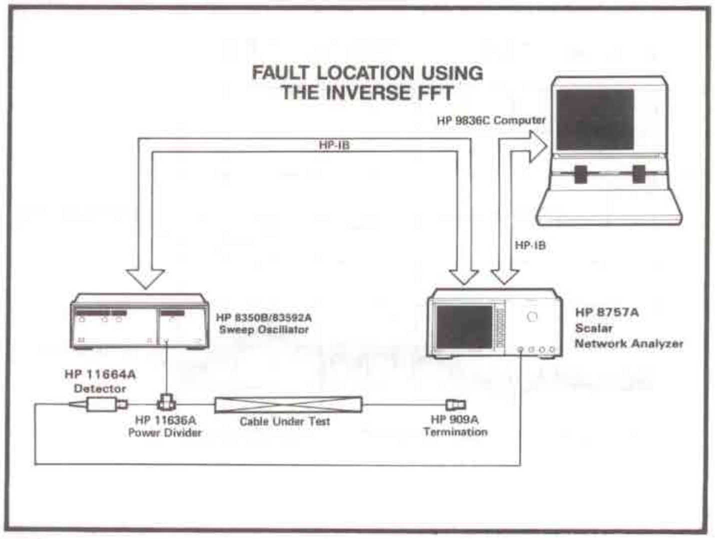
RIPPLE PATTERN

$$\Delta\Phi = f \times \Delta d \times \left(2 \times \frac{360^\circ}{V_p}\right)$$

- Vector Rotates as f is Swept
  - ➡ Ripple Pattern is Formed in Frequency Response
- Ripple is "Fast" When d is Large (Transmission Lines)

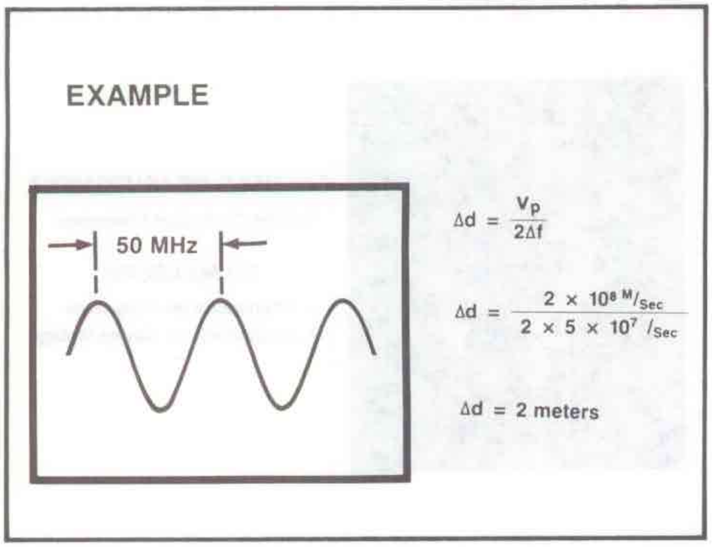
3283

It is possible to take advantage of the ripple pattern formed in transmission line measurements to perform another important measurement: fault location. The test setup shown here optimizes the formation of this ripple pattern, providing frequency domain data which can be converted to the distance domain using the inverse Fast Fourier Transform (FFT). This technique is called frequency domain reflectometry and it allows the operator to characterize impedance mismatches as a function of distance along the line. This is a valuable tool for troubleshooting lines, for example during installation and maintenance of communication, radar, or electronic countermeasure systems.



FAULT LOCATION USING THE INVERSE FFT

3285


EXAMPLE

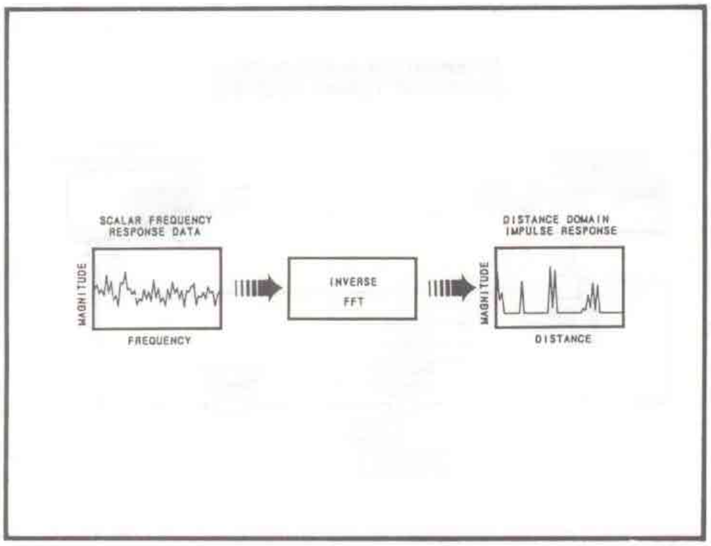
$$\Delta d = \frac{V_p}{2\Delta f}$$

$$\Delta d = \frac{2 \times 10^8 \, ^{M}/_{Sec}}{2 \times 5 \times 10^7 \, /_{Sec}}$$

$$\Delta d = 2 \text{ meters}$$

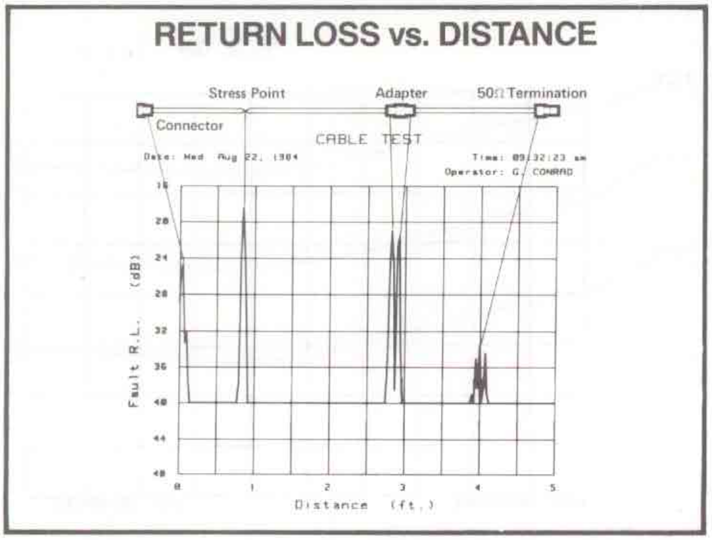
4158

With a single reflection from the line, you can measure the frequency response and then simply calculate the distance-to-fault. Example calculations are shown here.



3286

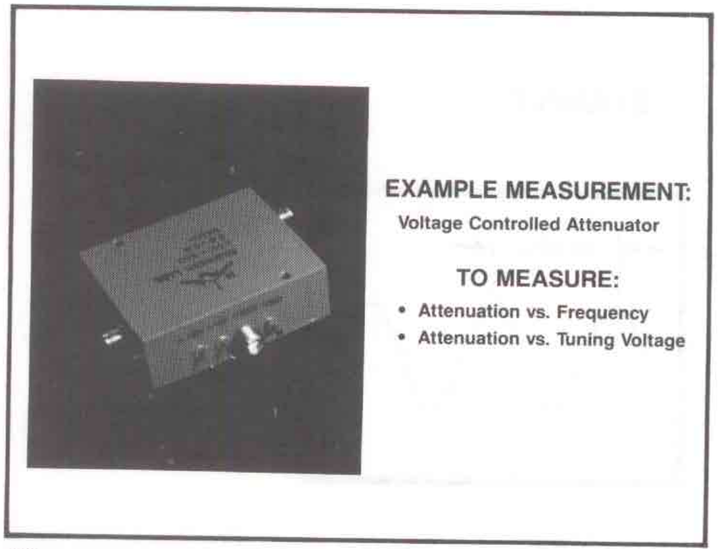
With multiple faults, the ripple pattern becomes more complex. We need the aid of the computer. By performing an inverse Fast Fourier Transform on frequency domain data, we convert the frequency domain information to its time domain equivalent. The time axis is then scaled by the velocity of propagation, and the result is the distance domain response. Mismatches appear as pulses whose location and magnitude are easy to read.


RETURN LOSS vs. DISTANCE

3287

Here we see the example cable with several mismatches lined up with its distance domain response. Notice how easily bad connections or faulty cable sections can be located. The HP 8757S automatic scalar network analyzer and the HP 85016 transmission line test software perform this measurement effectively.

The next broadband passive device example is another attenuator, this time, a voltage controlled attenuator. The attenuation is adjusted by simply adjusting the control voltage on the tuning input. The two measurements we wish to make on this device are attenuation versus frequency and attenuation versus control voltage.



EXAMPLE MEASUREMENT:

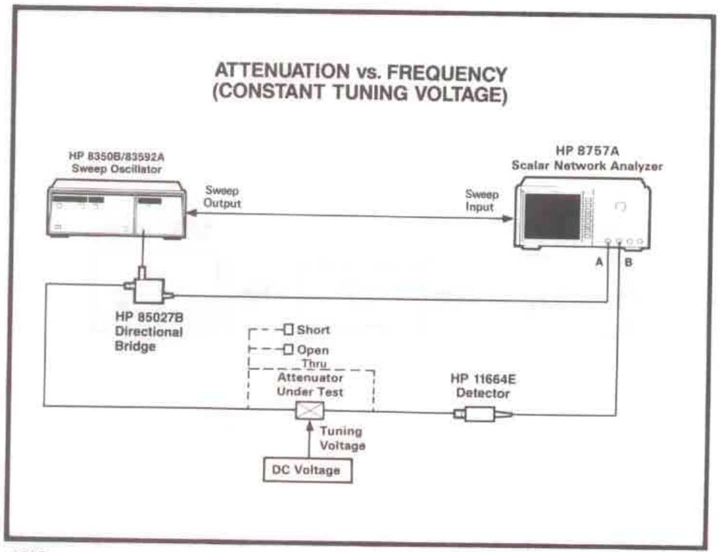
Voltage Controlled Attenuator

TO MEASURE:

- Attenuation vs. Frequency
- Attenuation vs. Tuning Voltage

3291

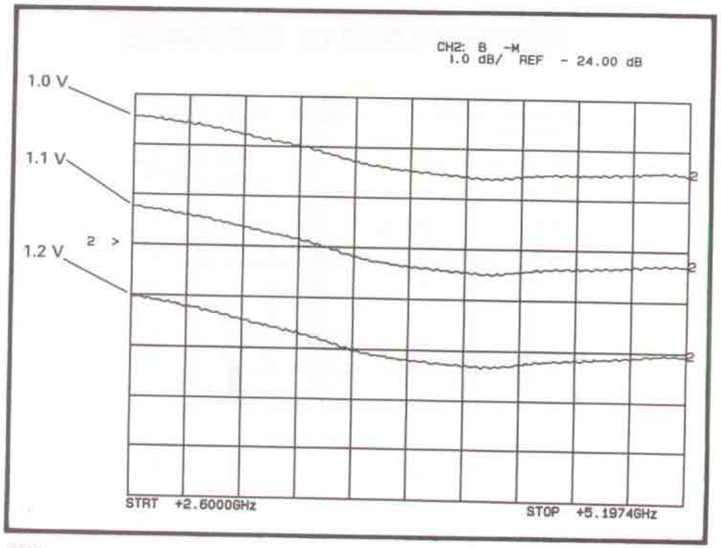
The first measurement is of frequency response at a constant tuning voltage. This attenuator operates from 2.6-5.2 GHz.



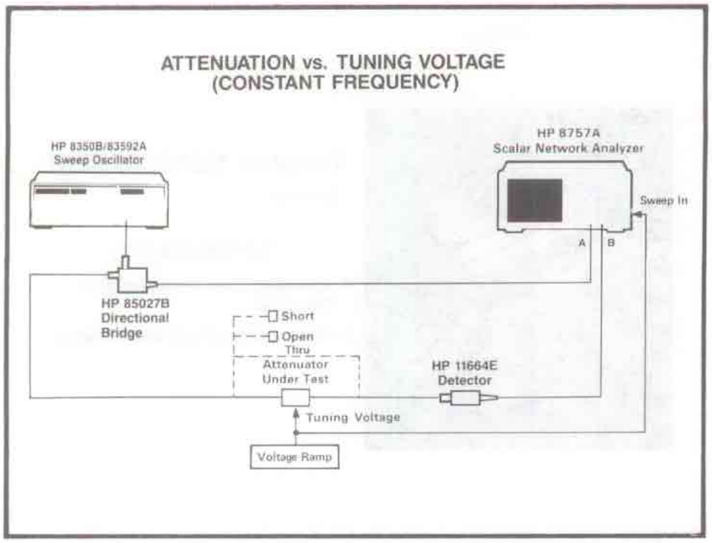
ATTENUATION vs. FREQUENCY
(CONSTANT TUNING VOLTAGE)

3292

Shown here is the attenuation vs. frequency for several values of tuning voltage. The entire frequency range can be observed as the tuning voltage is adjusted.



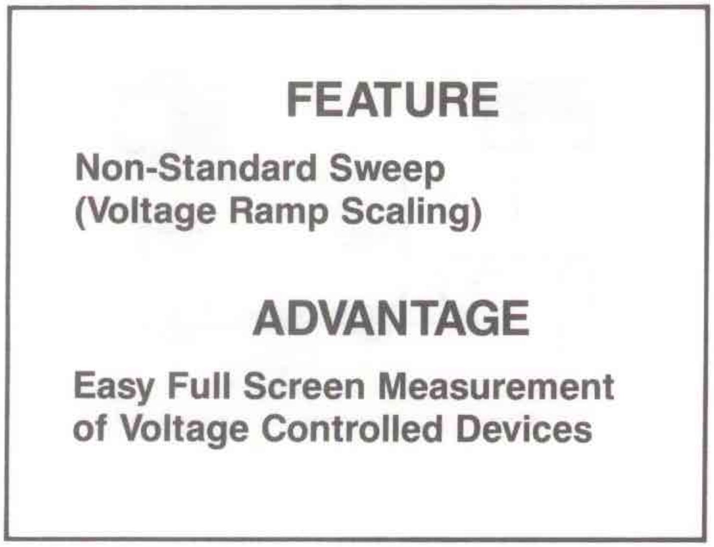
3293



ATTENUATION vs. TUNING VOLTAGE
(CONSTANT FREQUENCY)

3294

Another way of characterizing this device is by observing the swept voltage response while the microwave source is held at a constant frequency. The HP 8757A non-standard sweep mode is very useful here. On request, the HP 8757A can scale any voltage ramp in the 0-10 V range for full screen display. In this example, a 1-4 V triangle wave from a function generator is used to drive not only the VCA tuning input, but also the HP 8757A sweep input. The microwave source remains at one frequency.



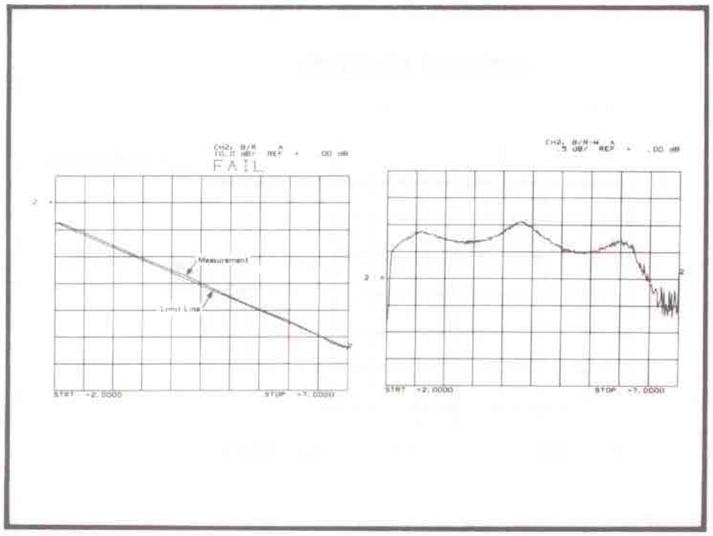
FEATURE

**Non-Standard Sweep
(Voltage Ramp Scaling)**

ADVANTAGE

**Easy Full Screen Measurement
of Voltage Controlled Devices**

3296

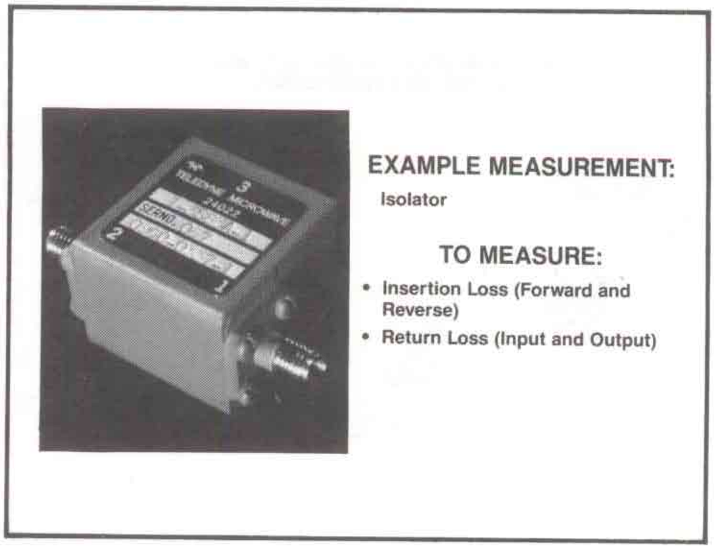


3090

The measurement shows how the attenuation increases linearly as the voltage increases. But this only shows the response at one frequency. Note that it would be difficult to see variations in linearity on this scale.

Using the sloped limit line feature of the HP 8757A, it is possible to measure VCA linearity. First, we enter a sloped line, and then compare it to the measured data. The difference between them can be viewed with high resolution.

An isolator is a broadband passive device which is designed to provide good output match with high reverse isolation. In this example, the input and output characteristics of this isolator will be measured in one setup.



EXAMPLE MEASUREMENT:

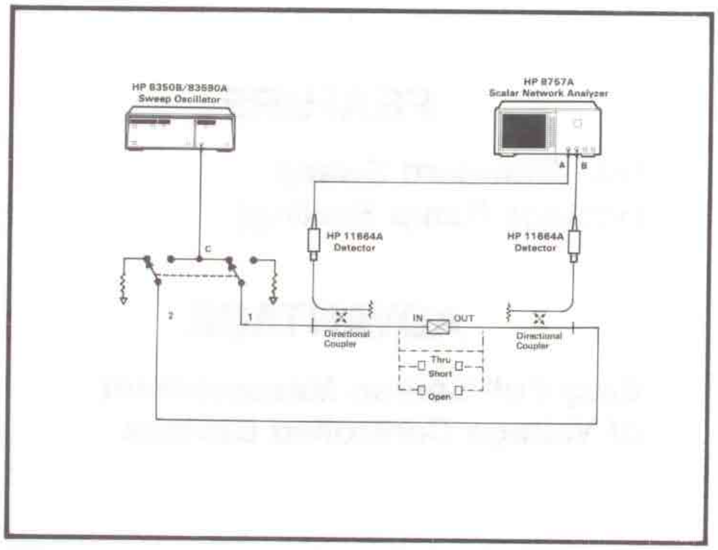
Isolator

TO MEASURE:

- Insertion Loss (Forward and Reverse)
- Return Loss (Input and Output)

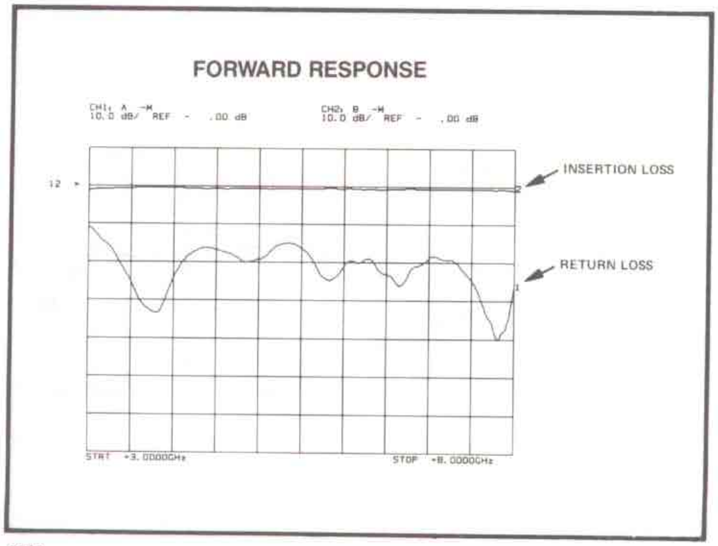
3098

This setup uses a switch and two directional couplers to provide two different paths of signal flow. When terminal 1 is connected to terminal C, the signal is incident on the input of the isolator, and the input return loss and forward insertion loss can be measured. When terminal 2 is connected to terminal C, the signal is incident on the output of the device and the output return loss and reverse isolation can be measured. Note that this switch provides termination for the unconnected switch position, which is necessary to avoid re-reflections.



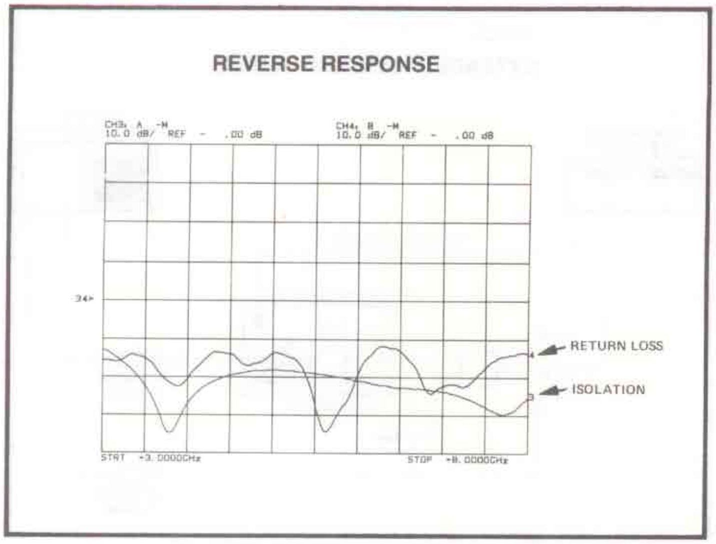
3298

This plot shows the forward response (C-1), return loss and insertion loss. Note that the forward insertion loss is relatively low.



FORWARD RESPONSE

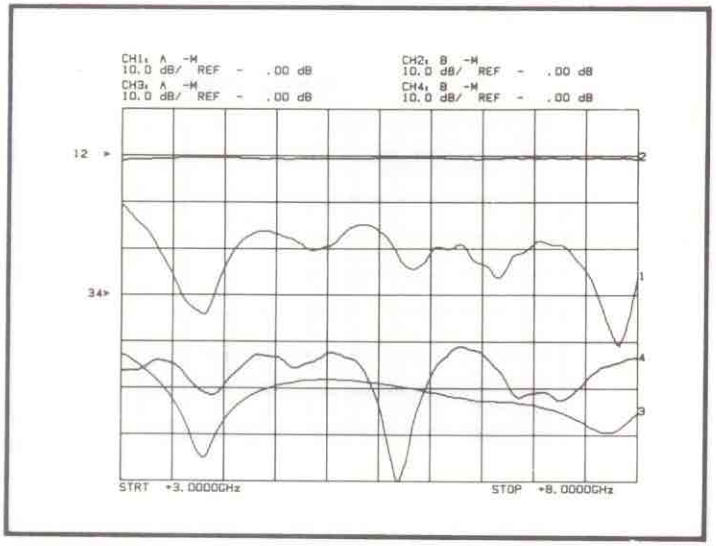
3299



REVERSE RESPONSE

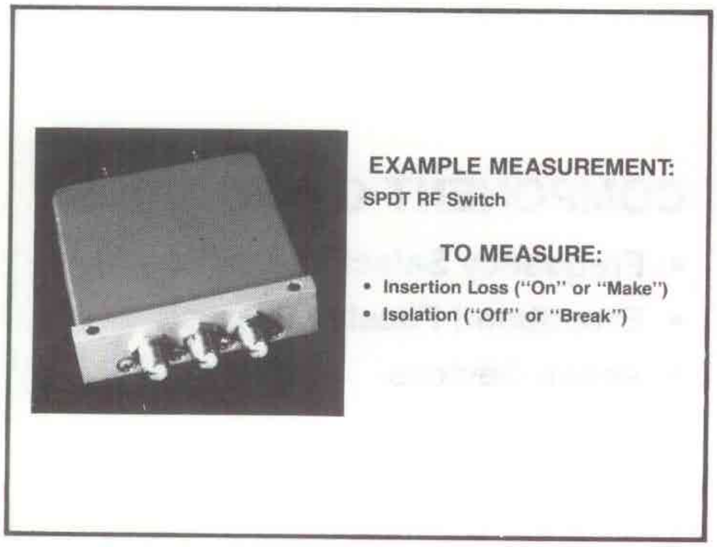
3300

This plot shows the reverse response (C-2), output return loss and reverse isolation. Note that the isolation is relatively high (20 dB).



3300

With the HP 8757A in this setup, it is possible to display all four parameters simultaneously. In this configuration, only the forward or the reverse traces are active. Using a PIN switch, and the HP 8757 alternate sweep mode, all four traces could be updated in real time.



EXAMPLE MEASUREMENT:
SPDT RF Switch

TO MEASURE:

- **Insertion Loss ("On" or "Make")**
- **Isolation ("Off" or "Break")**

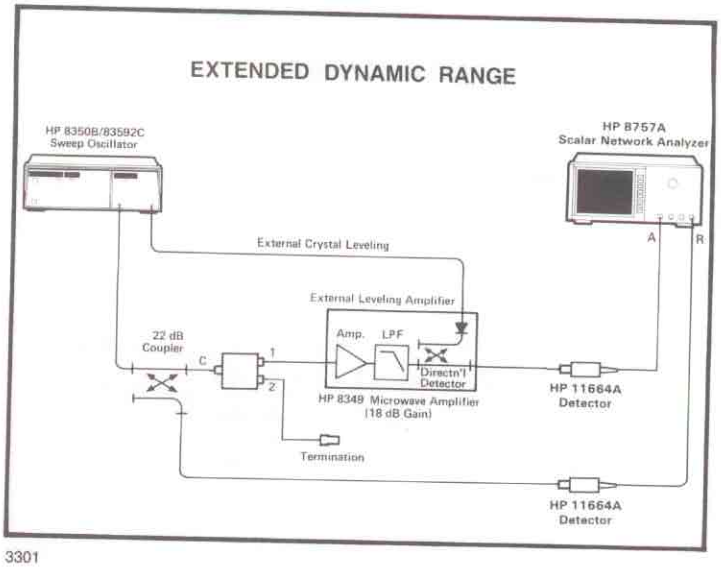
3097

Our last broadband passive device example is a single pole double throw switch to be tested from 2-18 GHz. We will measure the parameters at one terminal only, both insertion loss (with that terminal connected) and isolation (with that terminal unconnected).

Since switch isolation is often very high (>100 dB), an extended dynamic range setup is required to make this measurement. In this setup, an HP 8349A amplifier is inserted in the path of the switch position being measured (position 1 in this diagram).

With the C-1 connection made, we can measure the "on" insertion loss of position 1 as the ratio A/R.

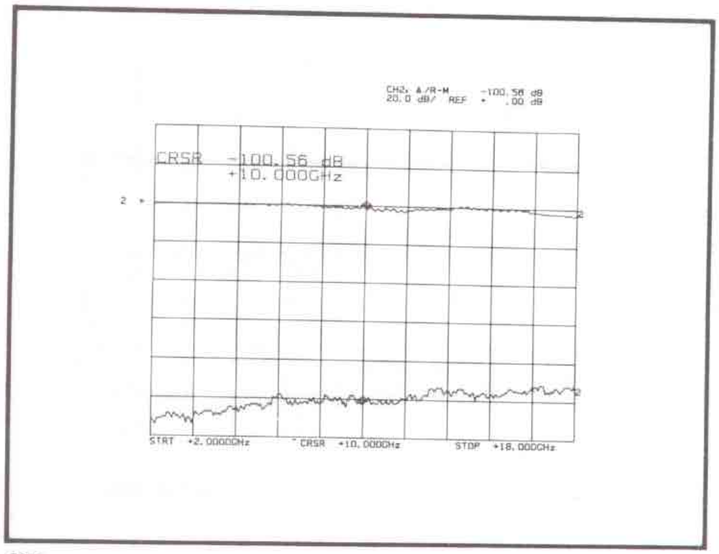
With the C-2 connection made, we can measure the "off" isolation of position 1, still the ratio A/R.



3301

This plot shows the resulting data, measuring 100 dB of isolation.

Note that the same measurements could be made for switch position 2 by inserting the amplifier between switch position 2 and the B detector.



3305

The next device category is active devices.

COMPONENT CATEGORIES:

- Frequency Selective Devices
- Broadband Passive Devices
- Active Devices

3306

AMPLIFIERS

- GaAsFET
- Bipolar
- TWT

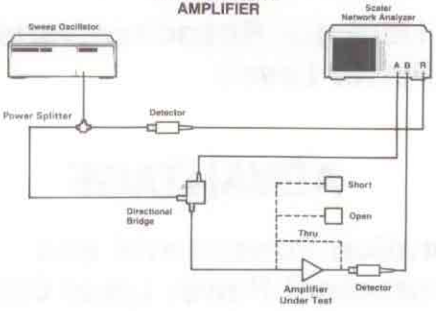
The most common active devices are amplifiers, and 3 common types of amplifiers are shown here. GaAsFET amplifiers have been designed to operate to very high frequencies (>40 GHz) and have good noise performance. Bipolar amplifiers typically provide higher output power, but the noise performance and frequency coverage are not as good as GaAsFET amplifiers. Travelling wave tube (TWT) amplifiers operate at very high power levels (e.g. 10 Watts).

AMPLIFIER PARAMETERS

- Gain and Gain Flatness
- Power
- Return Loss
- Reverse Isolation
- Phase Linearity/Group Delay
- Gain Compression (Saturation)
  - — Swept
  - — CW
- Harmonics
- Intermodulation Products
- Noise Figure

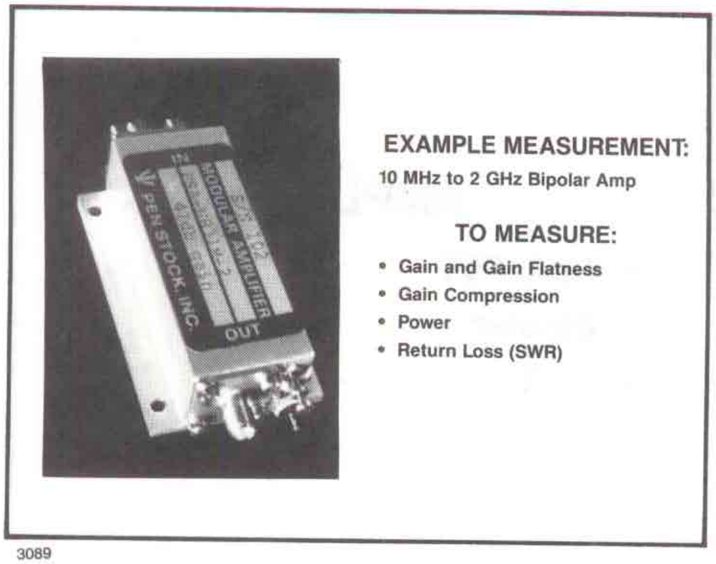
Amplifiers are characterized by many performance parameters, some of which are listed here. It is necessary to characterize amplifiers not only as a function of frequency, but also as a function of input power level. Some frequency and power response parameters can introduce distortion, but there are also other distortion parameters, such as harmonic and intermodulation distortion and noise figure. This discussion will include measurements of the scalar frequency response parameters and gain compression.

TYPICAL SCALAR MEASUREMENT: AMPLIFIER



A typical scalar measurement of an amplifier is shown here. Note that ratioing is used so that calibration can be maintained as the power level to the input is changed. Since the power change will appear in both output arms of the power splitter, the ratio remains unaffected. Without ratioing, the system would have to be recalibrated each time the power level was changed.

The first example measurement is a bipolar amplifier with about 40 dB of gain. We will use this example to illustrate many of the amplifier measurements.



EXAMPLE MEASUREMENT:

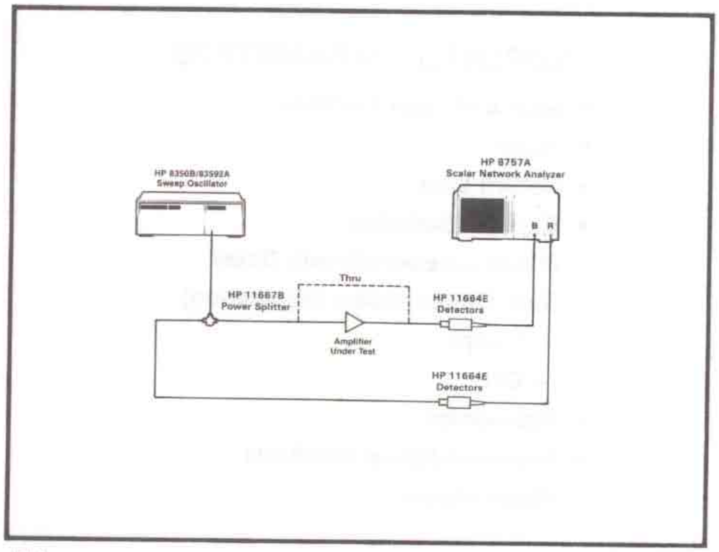
10 MHz to 2 GHz Bipolar Amp

TO MEASURE:

- Gain and Gain Flatness
- Gain Compression
- Power
- Return Loss (SWR)

3089

The measurement of gain is made with this setup. Notice that the calibration and the measurement will present different power levels to the B detector. The difference is the gain of the amplifier. It is important that the detectors' response not vary significantly as the incident power level is changed. This is specified as the dynamic accuracy of the detector and receiver.



3314

Good dynamic accuracy is an essential feature in amplifier measurement applications so that the difference in power level between the calibration and the measurement will not cause significant measurement error.

It is possible to avoid dynamic accuracy errors when measuring amplifiers with very high gain by inserting an attenuator after calibration. This can be used to minimize the change in power level between calibration and measurement. However, since the calibration does not include this attenuator, the frequency response of the attenuator will affect the normalized measurement.

FEATURE

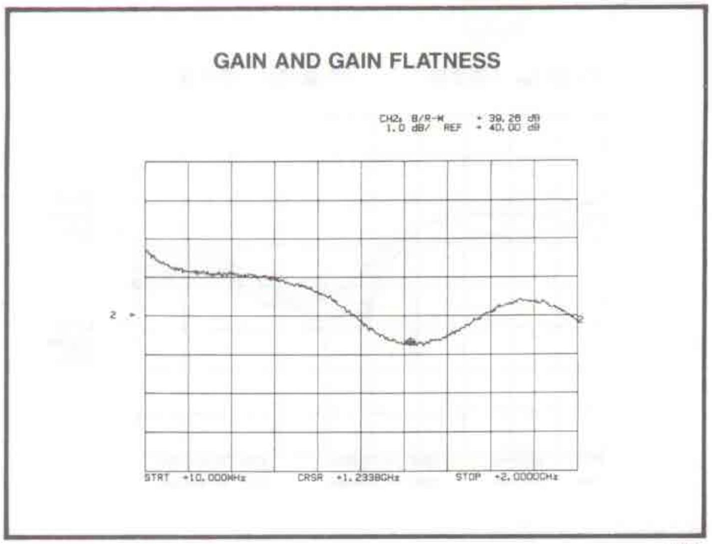
Good Dynamic Accuracy

(Low Detector Response Variations with Power Level)

ADVANTAGE

Calibration Power Level and Measurement Power Level Can Be Different Without Adversely Affecting the Measurement

3316



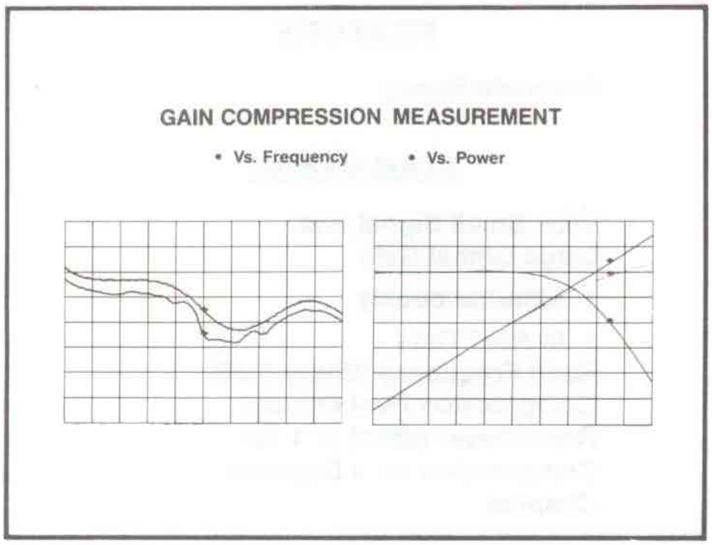
GAIN AND GAIN FLATNESS

CH2: B/R-M + 39.26 dB
1.0 dB/ REF + 40.00 dB

STRT +10.000MHz CRSR +1.2338GHz STOP +2.0000GHz

3315

This plot shows gain versus frequency. Cursor functions are useful in this measurement to determine max, min and peak-to-peak ripple.

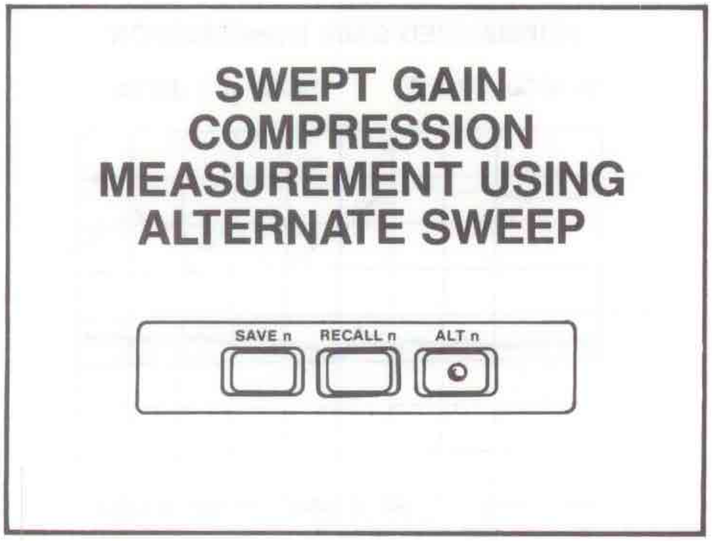


GAIN COMPRESSION MEASUREMENT

- Vs. Frequency
- Vs. Power

3320

The next parameter to measure on this amplifier is gain compression or how the amplifier behaves in saturation. There are several ways to characterize gain compression. First, swept gain compression measurements can be made by simply increasing the power level at the input of the amplifier and observing how the gain trace falls. Another way to view this response is to sweep the input power while remaining at a constant frequency. Let's perform these measurements on the bipolar amplifier.

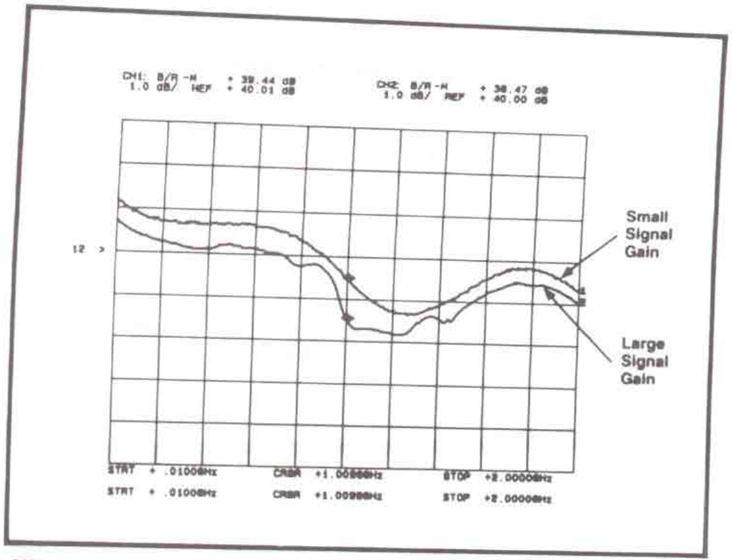


SWEPT GAIN COMPRESSION MEASUREMENT USING ALTERNATE SWEEP

3321

To make the measurement of swept gain compression, the alternate sweep function is very convenient. Recall that alternate sweep allows you to view the response for two different front panel states. In measuring filters, we found that alternate sweep enabled us to view two frequency ranges simultaneously in real time. For the amplifier application, we sweep the same frequency ranges at two different power levels.

The result is that you can view small signal gain and saturated gain at the same time. The source power simply alternates between two levels, and each response appears on one channel. As the power level is increased on one channel, you can see the gain trace drop as the amplifier saturates. At the same time you can still view the small signal gain in real time on the other channel. This makes gain compression measurements easy.



3322

The alternate sweep function allows simultaneous measurement of small signal gain and large signal (saturated gain) in real time. If adjustments or changes are made on the device, the operator can see how both the small and large signal gain are affected. The 1 dB gain compression point is often specified on amplifiers. This is the output power level at which the gain decreases by 1 dB. Using this measurement it is possible to see at which frequency gain compression first occurs. Using a third channel, the amplifier's maximum output power can be measured.

FEATURE

Alternate Sweep

ADVANTAGE

View Small Signal and Large Signal Gain

- **Simultaneously**
- **In Real Time**

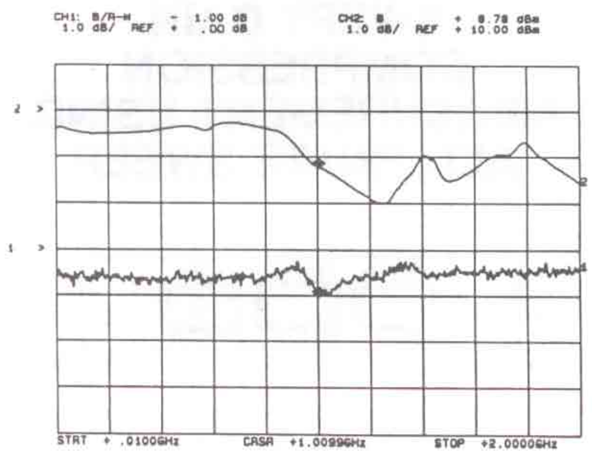
Read Frequency Where 1 dB Compression First Occurs

Read Power (dBm) at 1 dB Compression on a Separate Channel

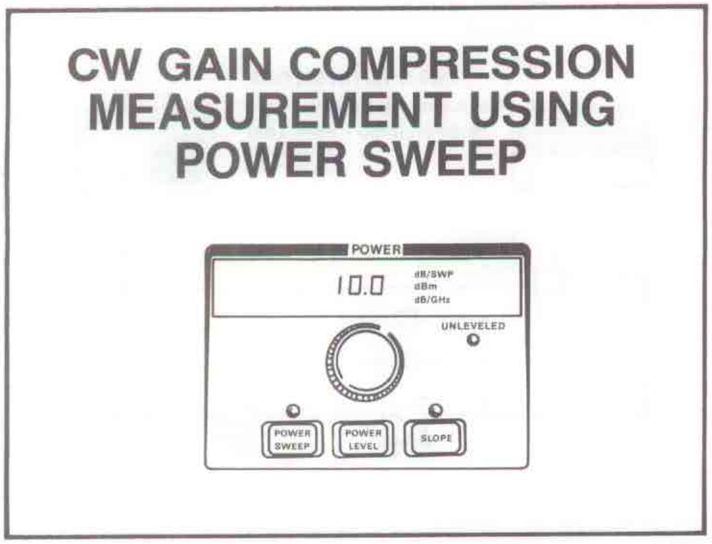
3323

Swept gain compression can also be measured without using alternate sweep. By normalizing with respect to small signal gain, and then increasing the power level, you can see the gain trace drop from down from a horizontal line. This normalization makes it easier to see the gain compression, and is very useful in final test applications. Again the frequency and power level at 1 dB gain compression can be read easily.

NORMALIZED GAIN COMPRESSION



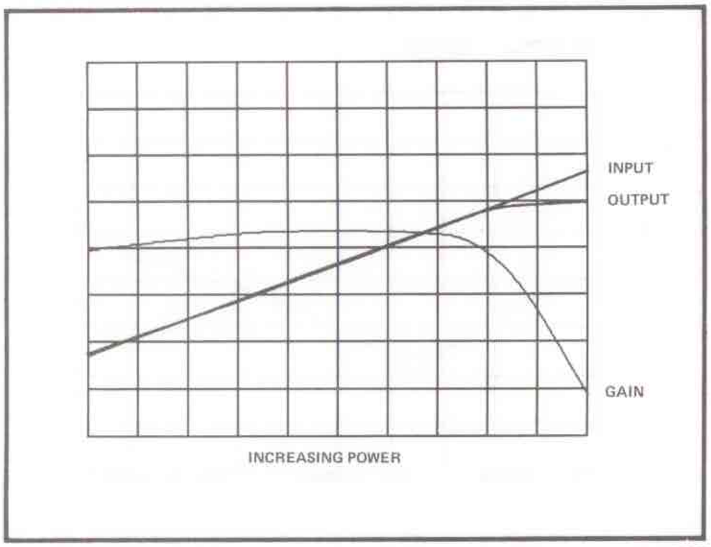
3324



CW GAIN COMPRESSION MEASUREMENT USING POWER SWEEP

3325

CW gain compression measurements can be made using the power sweep function of many HP swept sources. The power out of the source is swept linearly as the RF frequency remains constant.



3326

Now it is easy to see the rolloff in the gain, and the point at which the output power no longer linearly tracks the input power.

FEATURE

Power Sweep

ADVANTAGE

Show Gain vs. Input Power Level
Read Power (dBm) at 1 dB Compression

3328

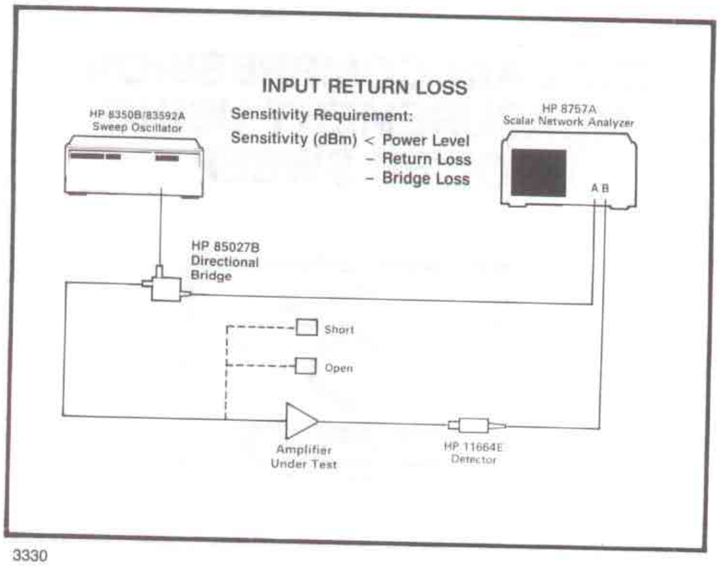
The power sweep feature gives you the capability of making effective gain compression measurements at a single frequency. Use alternate sweep to locate the first frequency to compress by 1 dB, and then power sweep to read the compression power level.

Amplifier input and output return loss are other important amplifier parameters that can be measured with scalar network analyzers. The setup for measuring input return loss is shown here. If the input return loss measurement is made at a very low power level (for example when measuring an amplifier with very high gain), the measurement can be limited by the sensitivity of the detectors used. The reflected signal being detected must be greater than the sensitivity of the bridge (or detector) that is detecting the reflected signal. This equation summarizes the sensitivity requirement. "Power level" is the test port power level, and "bridge loss" is any loss in the signal from the amplifier input to the detector (6 dB for a directional bridge).

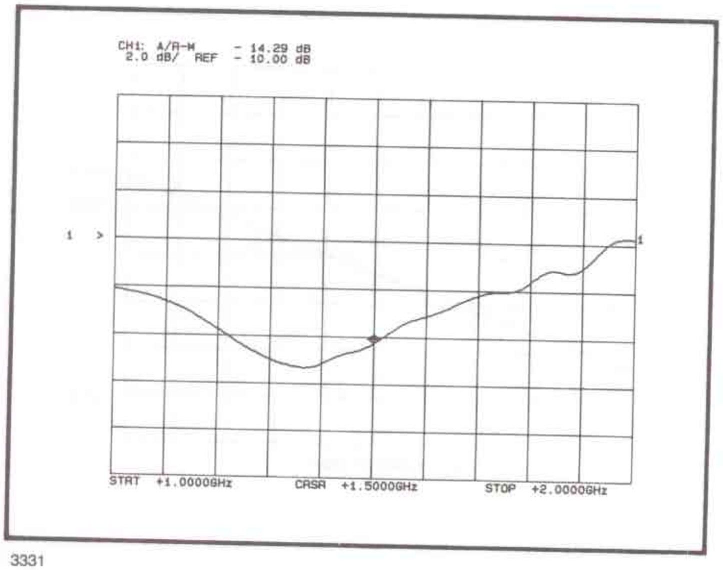
For the example amplifier, sensitivity was not a limitation, since the signal being detected (-45 dBm) is larger than the bridge sensitivity (approx. -60 dBm). If it were a limitation (e.g. for a higher gain amplifier tested at lower input power level), it may be necessary to test input return loss at a higher input power level. The amplifier may go into saturation, and we must assume that the amplifier has the same return loss in saturation. This assumption may not be valid.

Measurements of output return loss can also be made using this setup. Note that the amplifier is just turned around.

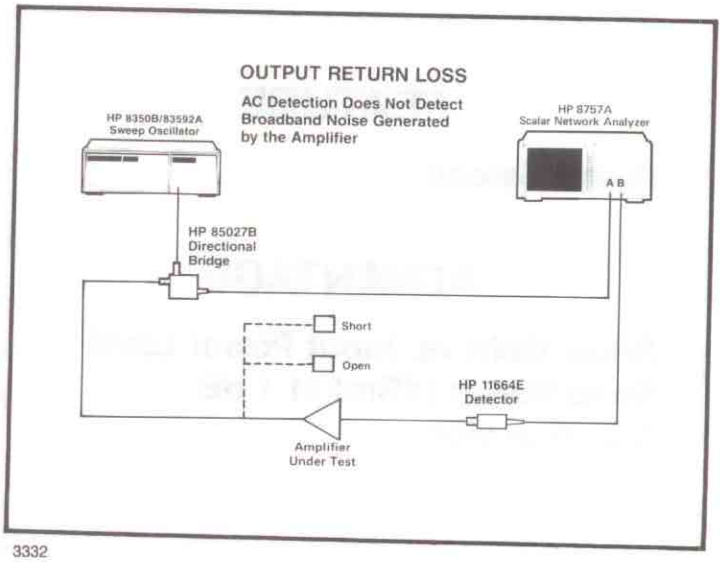
In some measurements, the broadband noise generated by the amplifier (not present in the source) may degrade the signal detected by the bridge. However, this is only a problem for DC detection since all signals present are detected, including the broadband noise. With AC detection, the noise is not modulated, so it is not detected, and accurate gain measurements are achieved.



3330

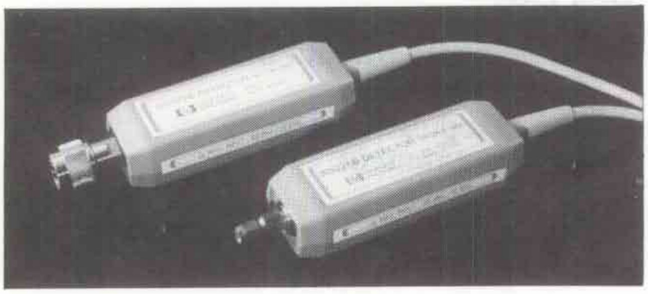


3331



3332

SWEPT POWER MEASUREMENTS USING DC DETECTION MODE

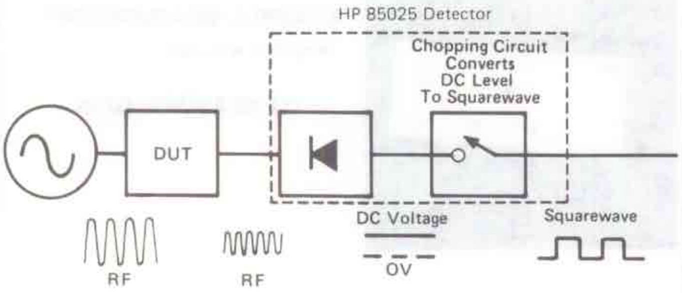


3329

Another common amplifier measurement is the measurement of output power (dBm) versus frequency. This measurement can be made accurately and quickly using the HP 85025A/B detectors in DC detection mode. A power meter still provides the more accurate power measurements, but the scalar analyzer provides swept frequency power measurements which can be accomplished more quickly.

(Power measurements can also be made in AC detection mode, but this is dependent on the RF modulation, which may vary.)

HP'S AC/DC DETECTION



3310

A review of AC/DC detection is helpful at this point to see which mode is more appropriate in amplifier measurements.

With AC detection, the detector responds only to signals that are modulated by a specific frequency (27.8 kHz for the HP 8757A/56A). Any unmodulated signals are not detected.

In DC detection mode, the diode provides a DC output voltage proportional to the power of all signals at the input, modulated or not. This signal is then chopped at a 27.8 kHz rate to simulate the signal provided by AC detection. This method of DC detection permits the use of the receiver's AC log amplifiers which provide fast response time in either AC or DC mode.

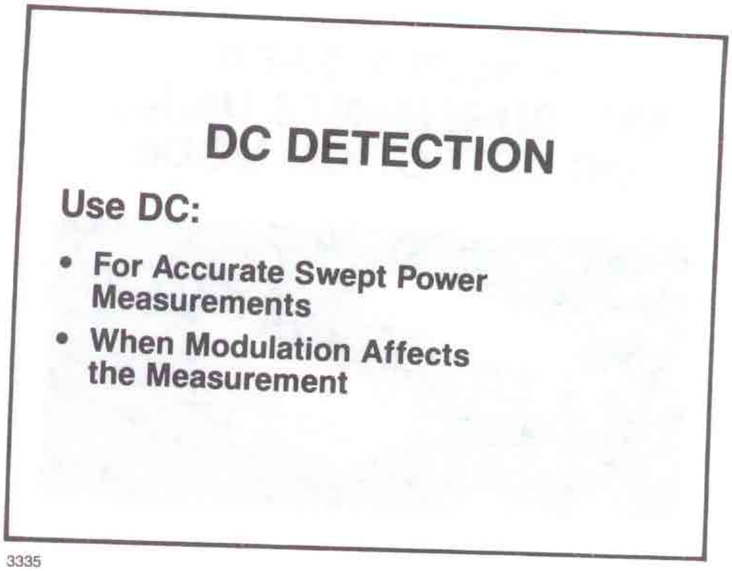
AC DETECTION

- For Accurate Relative Measurements Even in the Presence of:
  - Spurious Signals
  - Broadband Signals
  - Thermal Drift

3334

AC detection mode is ideal for accurate ratio measurements, and for measurements in the presence of broadband noise or other spurious signals. The effect of thermal drift is virtually eliminated.

DC detection is very useful for swept frequency power measurements, as already discussed, and for measurements that are adversely affected by modulation. One such amplifier, with automatic gain control (AGC), is shown in the following example.



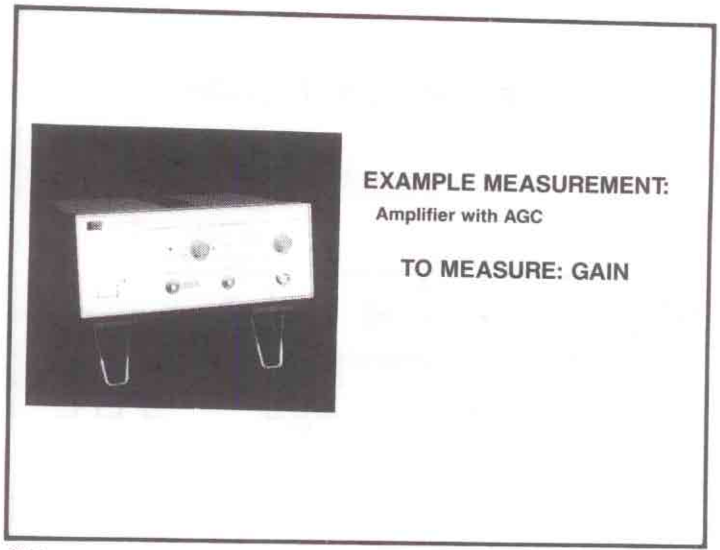
DC DETECTION

Use DC:

- **For Accurate Swept Power Measurements**
- **When Modulation Affects the Measurement**

3335

This amplifier includes an AGC. The user controls the output power with a front panel knob, and the amplifier adjusts its gain to provide that power at its output.



EXAMPLE MEASUREMENT:

Amplifier with AGC

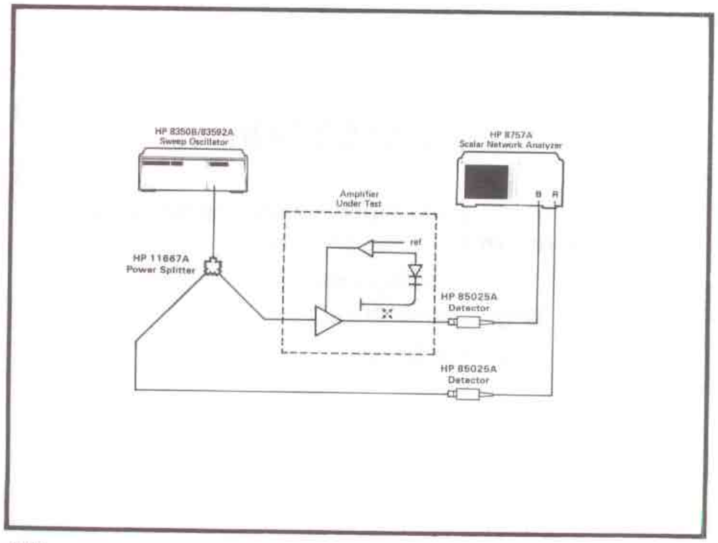
TO MEASURE: GAIN

3336

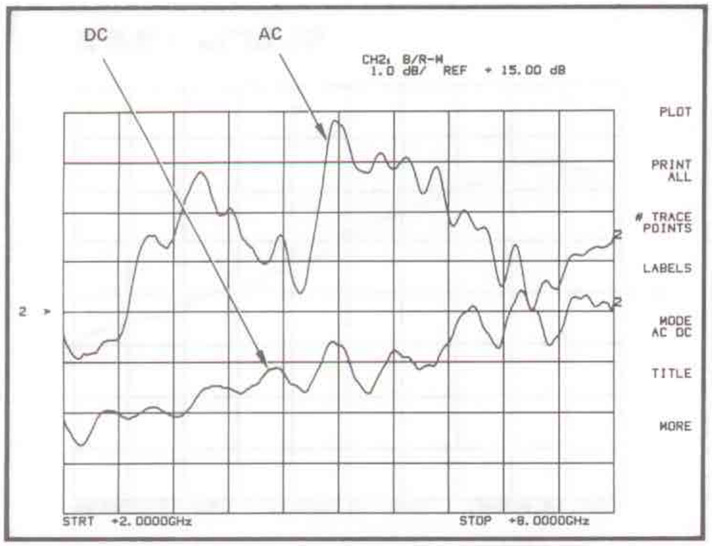
Again, ratioing is done to improve the source match and normalization is done with a "thru" connection. Within the amplifier, a sample of the output power is detected and compared to a reference voltage. The amplifier's gain is adjusted to provide the desired output power level over a whole range of input power levels. Note that we are using an HP 85025A detector to perform the gain measurement in both AC and DC detection modes.

In DC mode, the amplifier input and output are unmodulated. The detector chops this signal to form a 27.8 kHz square wave for the receiver.

In AC mode, the input to the amplifier is square wave modulated. The AGC tries to adjust its gain to track the modulation, but fails. The result is that a distorted square wave is sent back to the receiver, and errors result in the measurement.



3337



3338

This plot shows the data measured in both AC and DC modes. The higher reading in AC mode is the result of overshoot and ringing in the detected signal. DC detection provides a more accurate measurement in this application.

EXAMPLE MEASUREMENT:

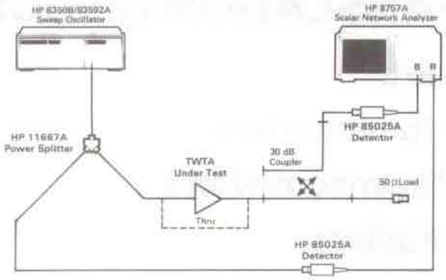
TWT Amplifier

TO MEASURE:

- Gain vs. Frequency

3339

The last active device measurement is of a 4-8 GHz traveling wave tube amplifier (TWTA). For this example, we will measure gain.

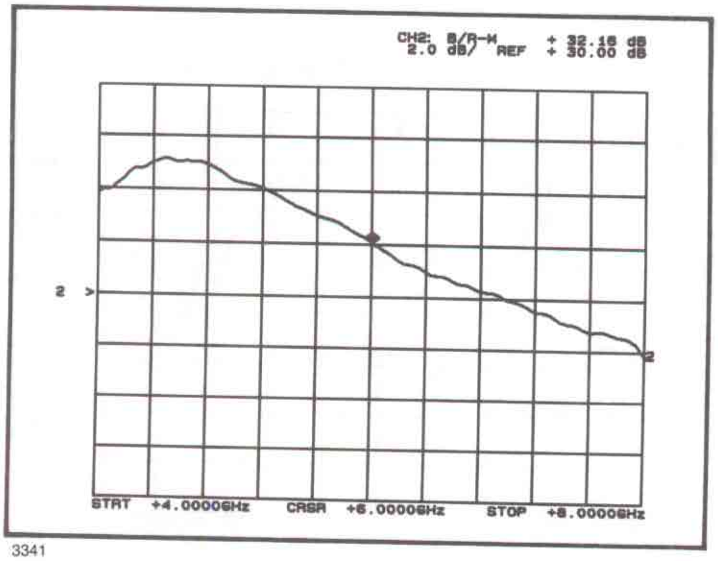


3340

This is the setup used for this measurement. Since the output power of the TWTA is so high (1W or +30 dBm), the output is sampled with a 30 dB coupler to avoid overdriving the B detector. Notice that the coupler's response is included in the calibration.

DC detectors are used to avoid using modulation which may affect the behavior of the TWTA.

The resulting gain data is shown here.



3341

The next component category is frequency translation devices. These are devices that change the frequency of an input signal.

COMPONENT CATEGORIES:

- Frequency Selective Devices
- Broadband Passive Devices
- Active Devices
- Frequency Translation Devices

3342

Mixers are the main focus of this discussion on frequency translation devices. They provide a signal at the output whose frequency is the sum or difference of the signals on the two inputs. Another device that translates frequency is the multiplier, which is used to provide a signal at its output whose frequency is double or triple the frequency at its input.

FREQUENCY TRANSLATION DEVICES

- Mixers
  - — Upconverters
  - — Downconverters
- Multipliers
  - — Doublers
  - — Triplers

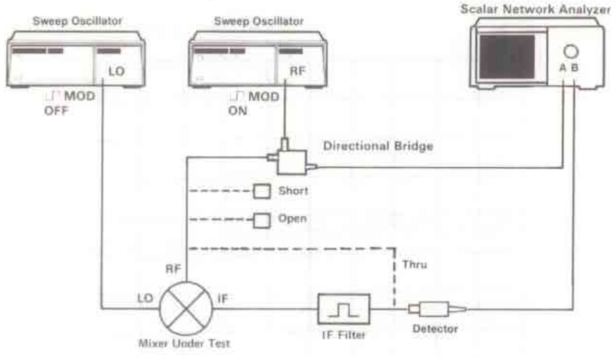
3343

MIXER PARAMETERS

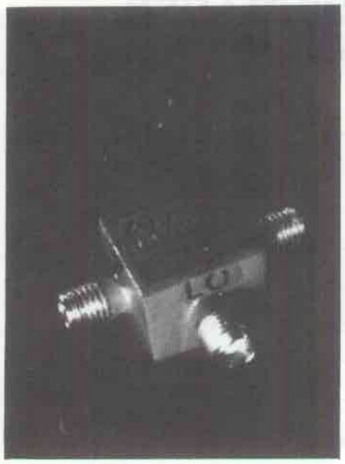
- Conversion Loss
- Power Out
- Isolation (e.g. LO Feedthrough)
- Return Loss (SWR)
- Phase Linearity/Group Delay
- Conversion Compression
  - — Swept
  - — CW
- Harmonics
- Intermodulation Products
- Noise Figure

3345

TYPICAL SCALAR MEASUREMENT: MIXER



3348



EXAMPLE MEASUREMENT:

Downconverting Mixer

TO MEASURE:

- Conversion Loss (Fixed LO)
- Conversion Loss (Fixed IF)
- Conversion Compression

3100

The mixer parameters we will discuss here are very similar to the amplifier parameters. The frequency response parameters include conversion loss (the power loss associated with the frequency translation) and return loss on all ports.

Like an amplifier, a mixer will saturate when the input power is increased. This causes the conversion loss to increase. This conversion compression can be measured in the same way gain compression is measured on amplifiers, either swept or CW. Harmonics, intermodulation products, and noise performance of mixers can also be characterized with a spectrum analyzer and noise figure meter.

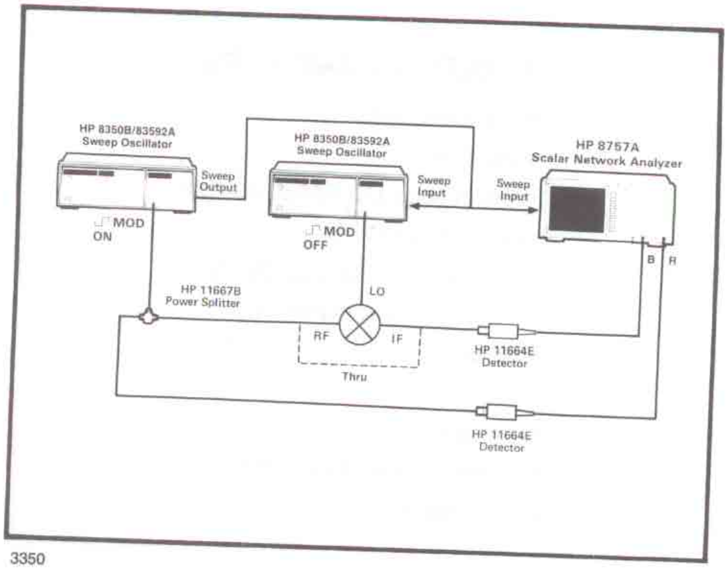
Shown here is a typical scalar measurement made on a mixer. Notice the need for two RF sources to stimulate two of the mixer ports. For example, if the mixer under test is being tested as a downconverter, then two sources are required, one to simulate the RF and one to simulate the LO (local oscillator). The mixing products will appear at the IF port. It may then be necessary to filter the IF before detection. (For more information on this "two tone" configuration, refer to HP Application Note 312-1.)

Note that the RF is modulated but the LO is not. AC detection mode will detect only the modulated signal, that is the signal from the RF port. The signal from the LO port (LO feedthrough) will be ignored. This makes AC detection a significant advantage in many mixer measurement applications.

This mixer's RF and LO operate from 2-12 GHz, and the IF operates from 10 MHz to 1 GHz. We will test the mixer for its use as a downconverter. We will show two kinds of conversion loss measurements. The first uses a fixed LO and a swept RF to produce a swept IF at the detector. In the second measurement, the IF is held constant by causing the RF and LO to sweep in unison with a fixed frequency offset.

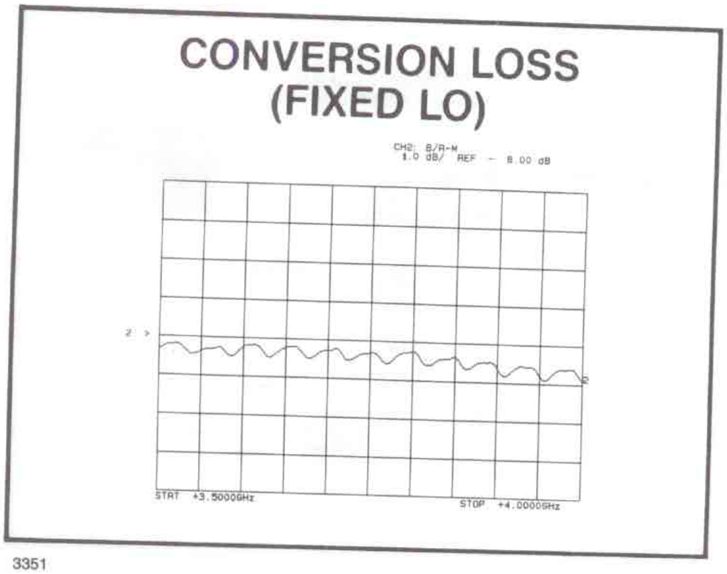
This setup is used to perform conversion loss and return loss measurements.

Notice that the calibration is done at a different frequency than the measurement. This means that the frequency response of the detectors will be different between calibration and measurement. It is therefore essential that the detector flatness (vs. frequency) be very good so that this error is minimized.



3350

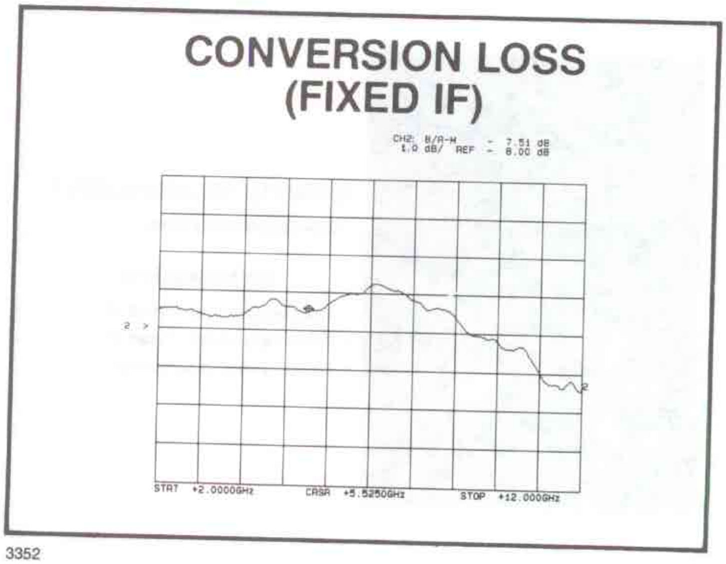
In this measurement, the LO is fixed at 3 GHz, and the RF is swept from 3.5 to 4.0 GHz. This sweeps the IF (the difference between the LO and the RF) from 500 MHz to 1 GHz. Note that the frequency annotation is for the RF and not for the IF, even though it is the IF that is actually being detected.



CONVERSION LOSS
(FIXED LO)

3351

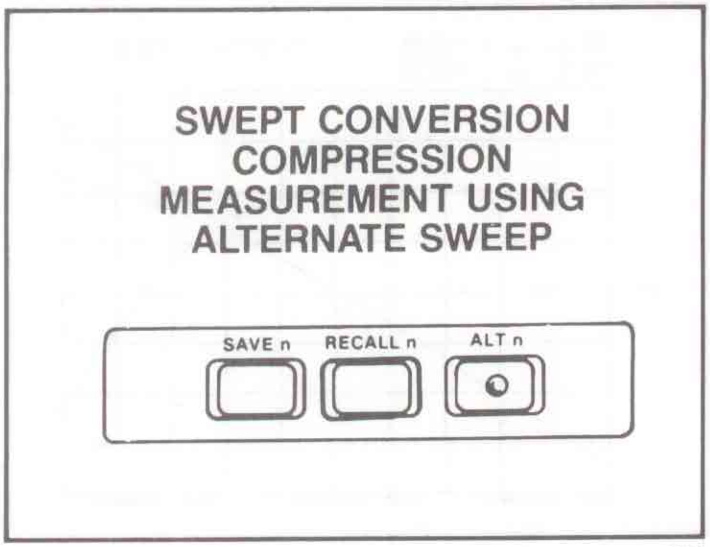
Since the IF range is only 10 MHz to 1 GHz, complete characterization of the mixer using the fixed LO method would require many steps to cover the entire 2-12 GHz range. By causing the RF and the LO to sweep together offset by a constant frequency (the IF), it is possible to make broadband sweeps. Here the IF is fixed to 100 MHz, with the LO sweeping from 2.1-12.1 GHz and the RF sweeping from 2-12 GHz. (A communication interface between the sweepers controls this dual sweep.)



CONVERSION LOSS
(FIXED IF)

3352

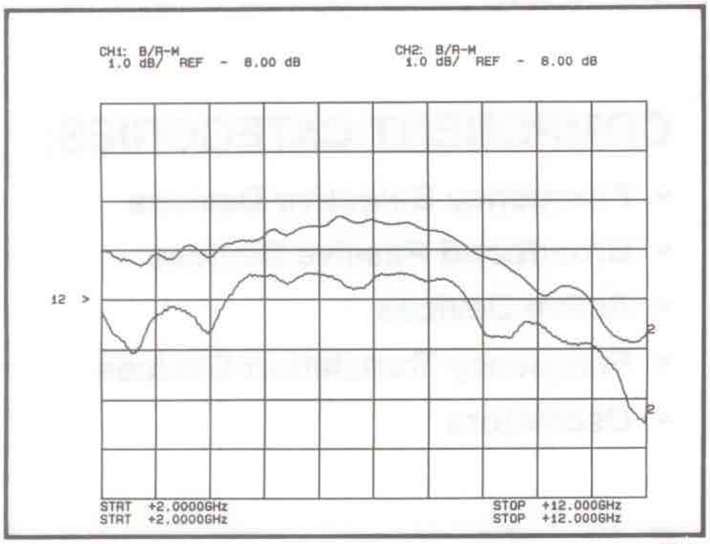
Now let's see how the conversion loss increases as the power level is increased.



SWEPT CONVERSION COMPRESSION MEASUREMENT USING ALTERNATE SWEEP

3354

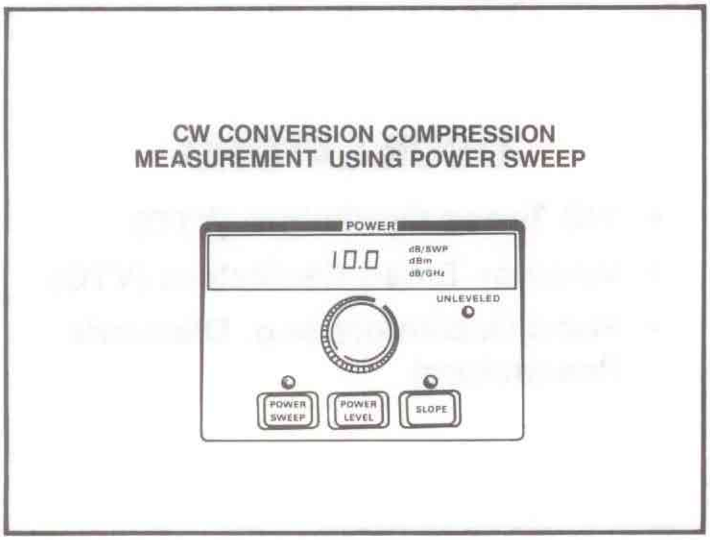
Just as in the amplifier example, we can measure swept conversion compression or compression versus input power level at a single frequency. Using alternate sweep we can alternate between small signal and large signal compression.



3355

Here we can see the conversion loss over frequency at two power levels, one trace is the small signal conversion loss and the other shows saturation and increased conversion loss.

Again, alternate sweep allows the operator to view both responses in real time, and to read the frequency at which compression first occurs.

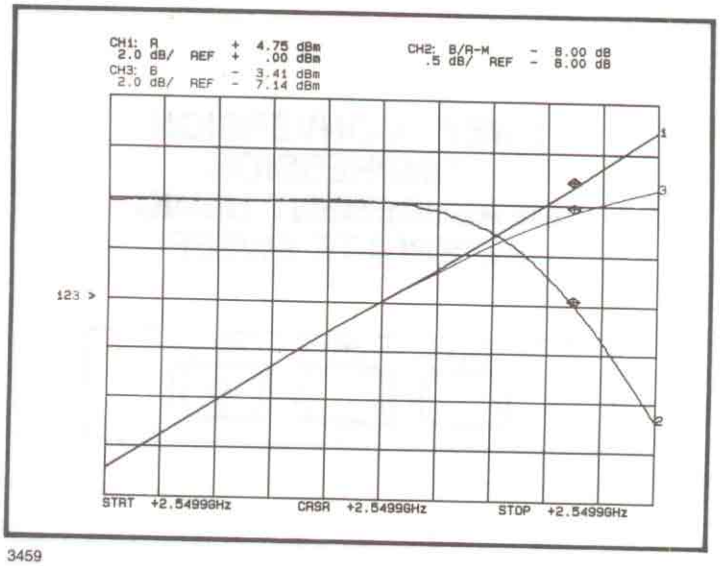


CW CONVERSION COMPRESSION MEASUREMENT USING POWER SWEEP

3458

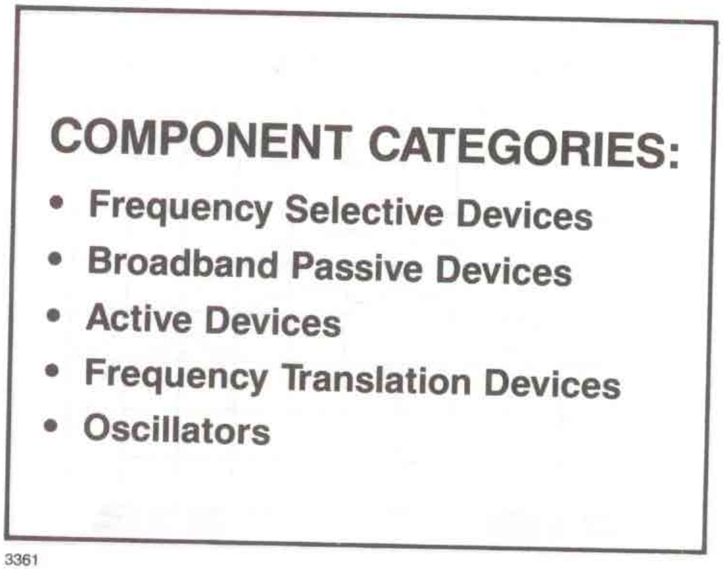
When the RF and LO are each kept at a single frequency, we can use the power sweep function to characterize conversion compression versus power level.

With power sweep, the RF power is increased linearly and conversion loss can be viewed as a function of power. Note that when saturation is reached, the IF power (B) no longer tracks the RF power (R), and the conversion loss (B/R) increases.



3459

Oscillators are the next component category.

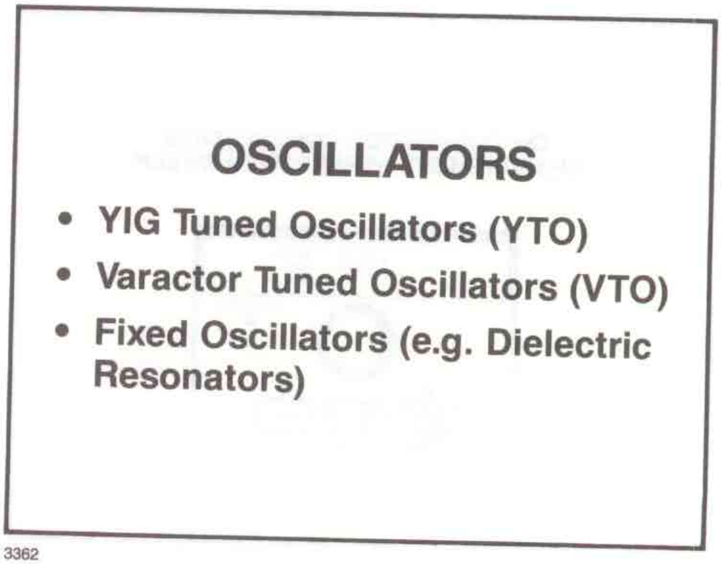


COMPONENT CATEGORIES:

- Frequency Selective Devices
- Broadband Passive Devices
- Active Devices
- Frequency Translation Devices
- Oscillators

3361

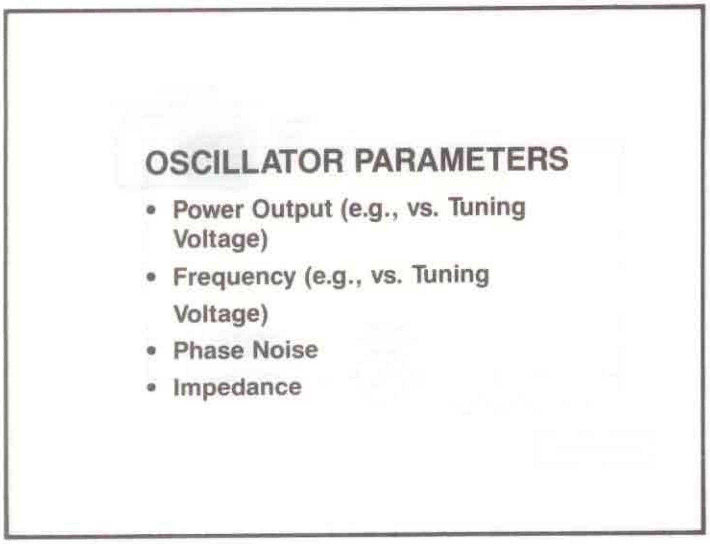
There are three common types of oscillators: YTO's, VTO's, and fixed oscillators.



OSCILLATORS

- YIG Tuned Oscillators (YTO)
- Varactor Tuned Oscillators (VTO)
- Fixed Oscillators (e.g. Dielectric Resonators)

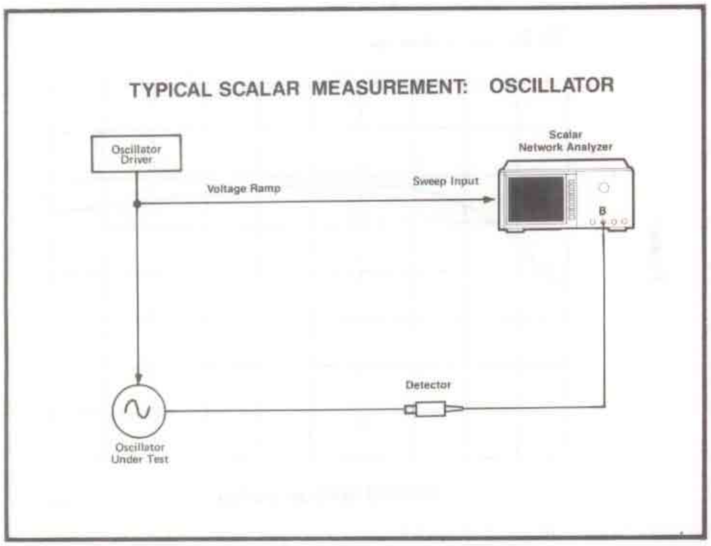
3362



OSCILLATOR PARAMETERS

- Power Output (e.g., vs. Tuning Voltage)
- Frequency (e.g., vs. Tuning Voltage)
- Phase Noise
- Impedance

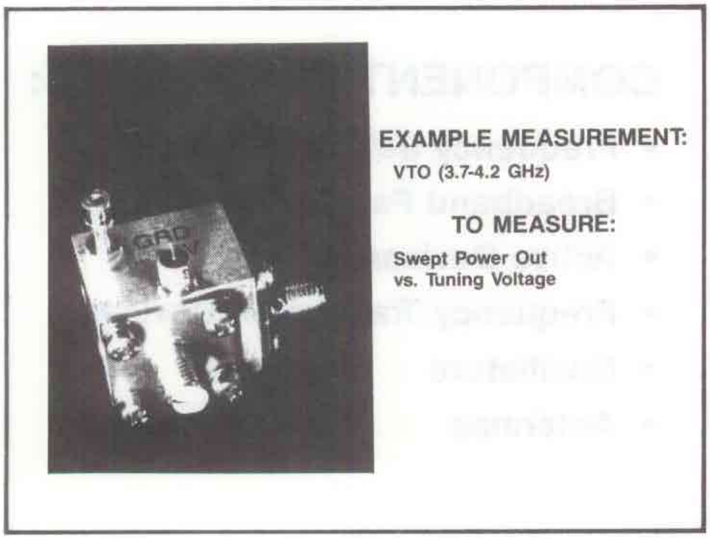
Some of the common oscillator parameters are shown here. Scalar network measurements are best suited for the measurement of swept output power as a function of tuning voltage or current.



TYPICAL SCALAR MEASUREMENT: OSCILLATOR

This setup shows the typical configuration for an oscillator measurement. Note that no external source is required to stimulate the device since the oscillator generates its own RF power.

Power measurement accuracy is perhaps the most critical feature of an oscillator measurement system. A feature that offers great convenience for testing tuned oscillators is the ability to use any voltage ramp to drive the display of the analyzer. The HP 8757A non-standard sweep function is ideal for this application.



EXAMPLE MEASUREMENT:

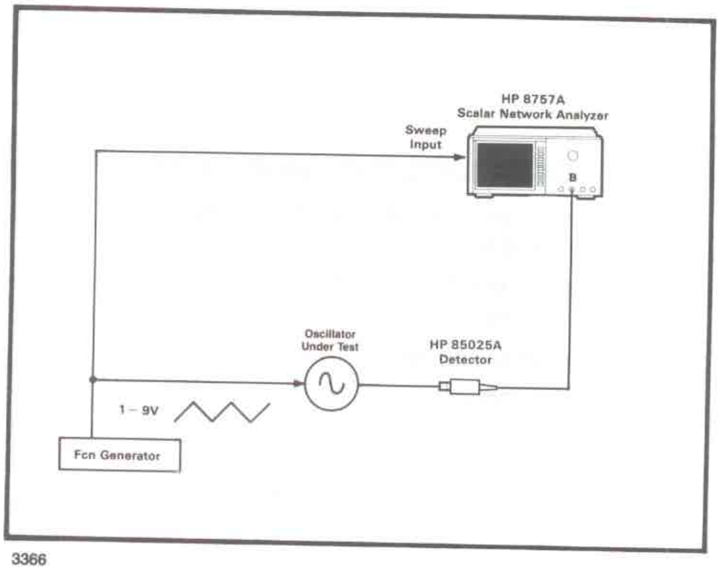
VTO (3.7-4.2 GHz)

TO MEASURE:

Swept Power Out vs. Tuning Voltage

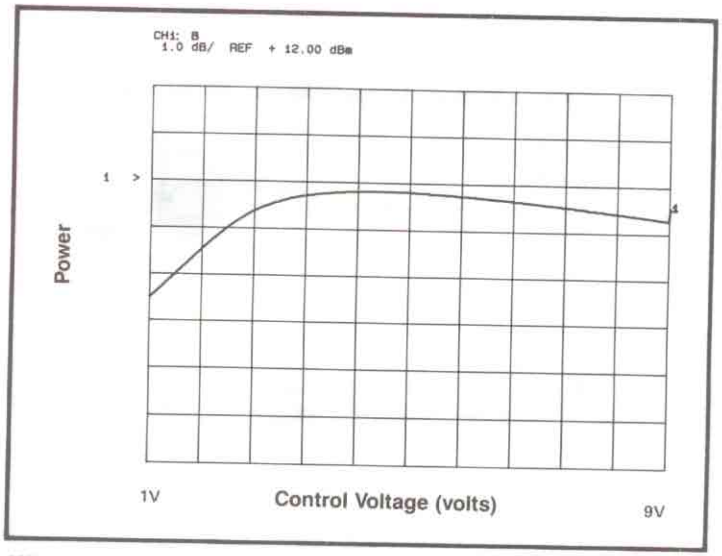
This example is a varactor tuned oscillator, and will be characterized by output power versus tuning voltage.

The setup includes a function generator to provide the voltage ramp (triangle wave) for the tuning input of the oscillator and for the sweep input of the analyzer. Notice that DC detection is used since the oscillator output is not modulated.



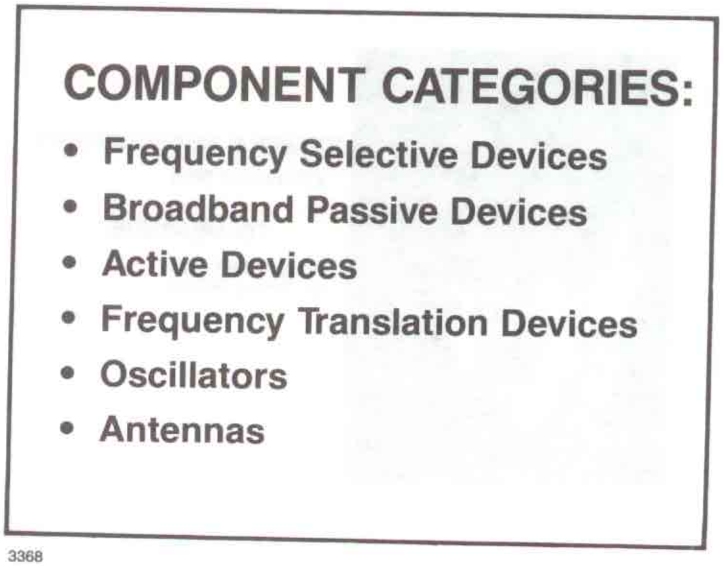
3366

The resulting plot shows power versus tuning voltage. A frequency counter could be used to see how frequency varies with tuning voltage. If the oscillator frequency is a linear function of tuning voltage, then the power versus voltage plot could be scaled to show power versus frequency.



3367

The final device category is antennas.



COMPONENT CATEGORIES:

- Frequency Selective Devices
- Broadband Passive Devices
- Active Devices
- Frequency Translation Devices
- Oscillators
- Antennas

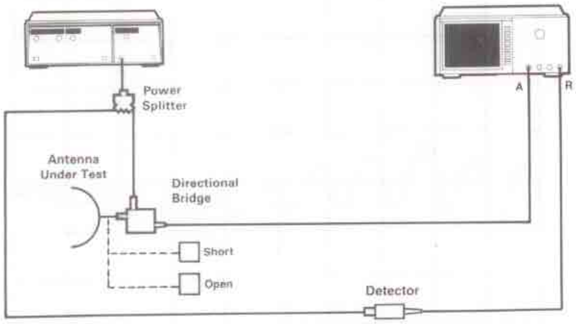
3368

ANTENNA PARAMETERS

- Return Loss
- Radiation Pattern

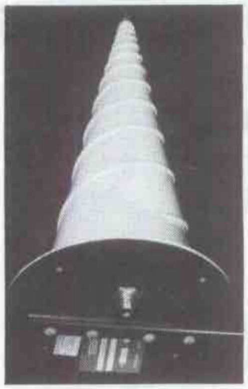
3369

Antennas are characterized by return loss and radiation pattern. Swept return loss measurements can be made using scalar network analysis.



3515

A typical antenna return loss measurement is shown here. Because antenna measurements are often made in the presence of spurious signals, AC detection provides a significant advantage. Since spurious signals are not modulated by 27.8 kHz, they will not be detected in AC detection mode.



EXAMPLE MEASUREMENT:

Antenna on Top of a Tower

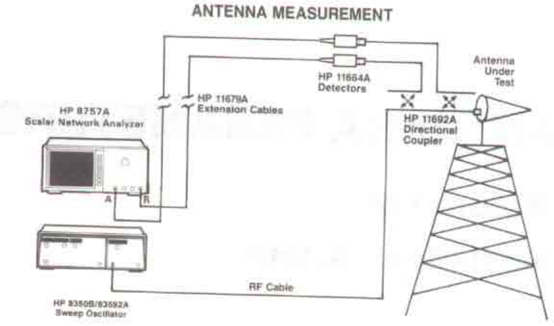
TO MEASURE:

Return Loss (SWR)

3426

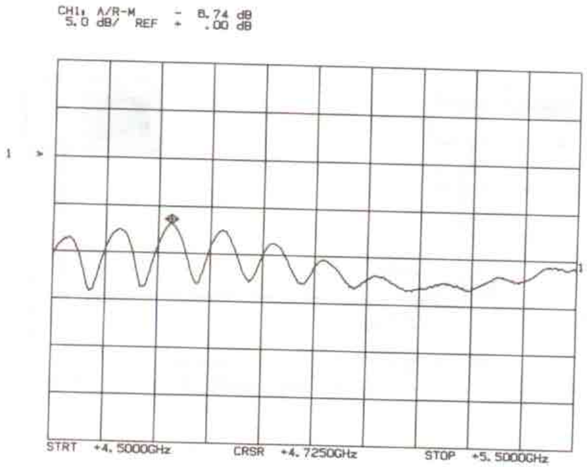
As an example, we will measure the return loss of this antenna. The antenna is situated in a remote location, about 20 feet from the test equipment.

As shown here, the antenna is tested, without the need to lift heavy instruments up the tower to the antenna. The detector extension cables allow the detectors to be located far from the instruments with no degradation in performance. Note also that the incident and reflected signals are sampled using a dual directional coupler. In this application, ratioing removes the effects of the RF cabling from the source to the coupler.



3461

The resulting data plot shows the return loss from 4.5 to 5.5 GHz. This is a very important check to make sure that the antenna is not shorted before high power is delivered to it.

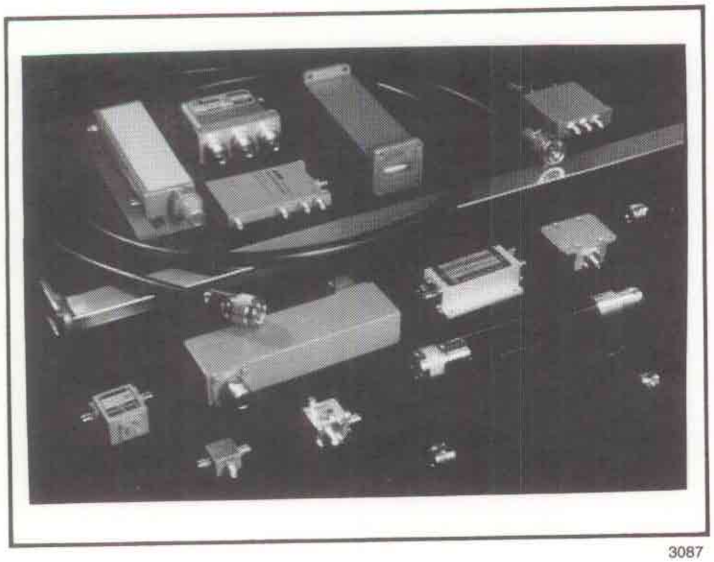


3374

If higher power is required at the test port, an amplifier such as the HP 8349 can be used. The HP 8349 microwave amplifier can deliver up to +20 dBm from 2-20 GHz.

Use the HP 8349 Amplifier
for Higher Power at the Test Port

3375



3087

There are many applications of scalar measurements. This section of the seminar has shown some of them. In the next section, we will see how automating scalar measurements can improve efficiency and provide more accurate results.