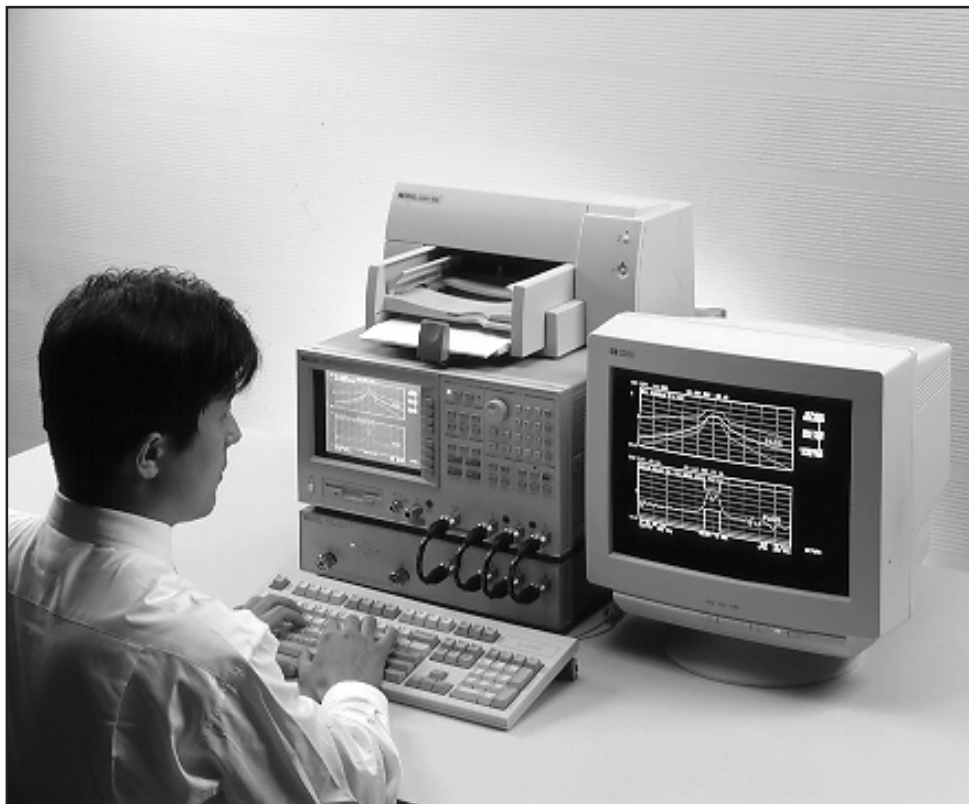# Network, Spectrum, and Impedance Evaluation of Electronic Circuits and Components

Application Note 1308-1

HP 4395A/HP 4396B
Network/Spectrum/Impedance
Analyzer

Introduction

With the current trends requiring higher performance, smaller physical size, lower cost, and higher reliability, fast cycle time is an increasingly important part of the product design. This is true not only in the consumer, but also in the communication and data processing industries.

As shown in Figure 1, the development procedure involves designing the overall architecture, evaluating electronic components, building prototypes, and evaluating circuit performance. From the design point of view, it is essential to measure the impedance characteristics of electronic components such as capacitors, inductors, or other devices at the actual working condition. An impedance analyzer makes it easy.

After making a prototype, a review of the circuit operation requires measurement of the following parameters: harmonics, noise, transmission characteristics, and reflection characteristics. The vector network analyzer, and the spectrum analyzer must be used for making these measurements. The HP 4395A/ HP 4396B Network/Spectrum/ Impedance Analyzer Family combines three analyzer functions in one instrument. This application note describes how the HP 4395A/96B can be used to contribute fast cycle time for product development.
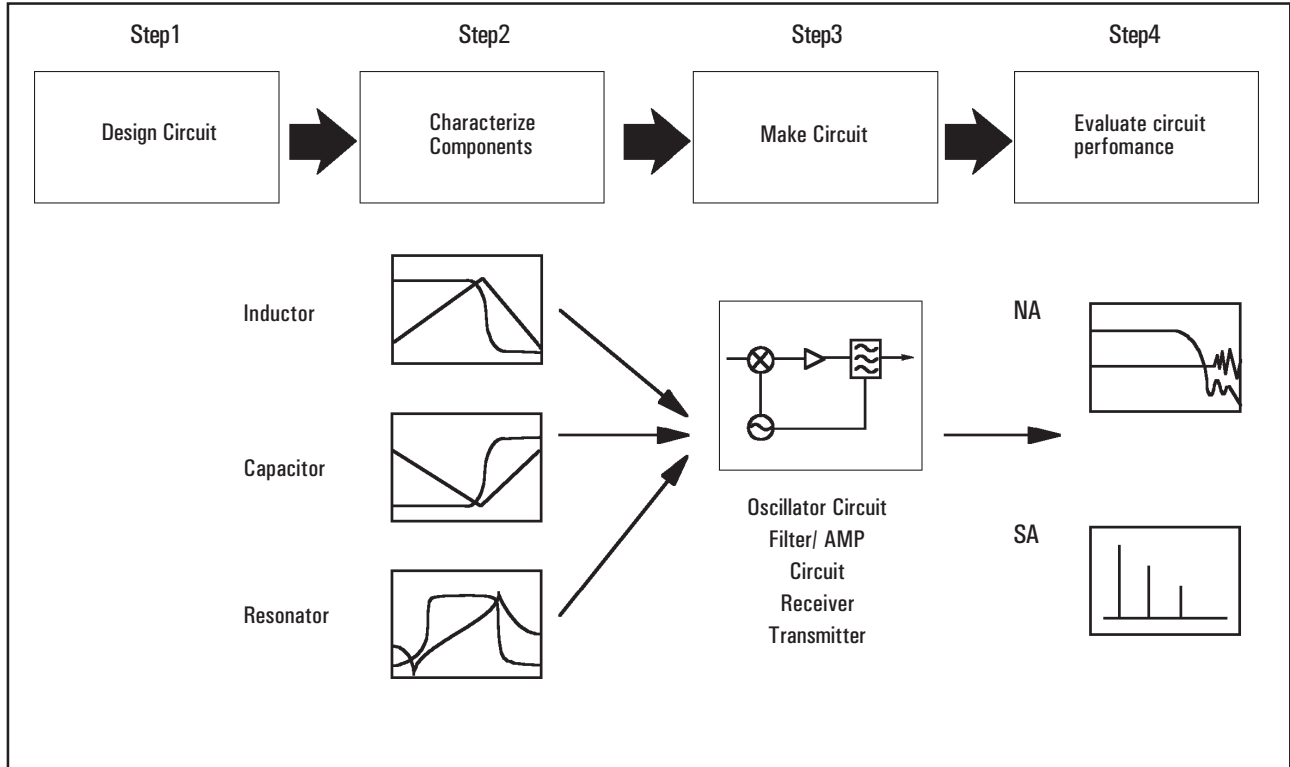

Figure 1. Circuit Development Process

The HP Combination Analyzers have the following features

• **Three analyzers in One box**

As the name implies, the HP 4395A/ HP 4396B Network/Spectrum/ Impedance Analyzer Family can perform vector network, spectrum, and (optional) impedance measurements. The HP combination analyzer family does not compromise vector network, spectrum, or impedance performance. It is a breakthrough in test instruments, giving you outstanding performance as a full-capability combination analyzer. Precision measurements and improved efficiency are possible with minimal training. Compared with using separate instruments, the HP 4395A/96B will save equipment cost and bench space.

• **Vector Network Analyzer Performance**

The HP Combination Analyzer Family offers you fast measurement with wide dynamic range. Transmission and reflection data can be provided with an optional Reflection/ Transmission Test Set or optional S-Parameter Test Set.
As a vector network analyzer, the HP 4395A operates from 10 Hz to 500 MHz. The HP 4396B operates from 100 kHz to 1.8 GHz.

• **Spectrum Analyzer Performance**

The HP Combination Analyzers, designed with new digital techniques, outperform traditional analog spectrum analyzer. They feature a Fast Fourier Transform (FFT) digital-signal processing (DSP) technique for 20 to 100 times faster narrow-band spectrum measurement, when compared to swept-tuned spectrum analysis. The analyzer's stepped FFT technique (HP 4395A: all RBWs, HP 4396B: 1Hz to 3kHz RBW) breaks the speed barrier to give you lower noise floors without sacrificing speed. In addition, low phase noise provides improved signal resolution. Option 1D6 (The Time Gated Spectrum Analysis Function) performs accurate burst signal analysis for burst-modulated signal evaluation.
As a spectrum analyzer, the HP 4395A operates from 10 Hz to 500 MHz. The HP 4396B operates from 2 Hz to 1.8 GHz.

• **Impedance Analyzer Performance**

When equipped with Option 010 and the HP 43961A, HP Combination Analyzers can perform direct impedance measurements. Measurement parameters such as $|Z|$, θ, C, L, Q, D and more can be displayed directly on the color display. A built in lumped equivalent circuit function aids circuit modeling and simulation.
As an Impedance Analyzer, the HP 4395A operates from 100 kHz to 500 MHz. The HP 4396B operates from 100 kHz to 1.8 GHz.

• **Other Useful Functions**

HP IBASIC, a subset of the HP BASIC programming language, is included with the standard HP 4395A/96B. HP IBASIC is extremely powerful and easy to use. It can be used for automated testing, analysis of measurement results, or control of external equipment via HP-IB. Files such as instrument state files, TIFF files, and data files can be transferred via HP-IB to the controller/PC (host), which can easily manipulate the files. Usability and productivity are improved through features such as the DOS supported Floppy Disk Drive, the list sweep function, the marker function, as well as the limit line function.

Table 1. HP 4395A Major Specification

Network Analyzer Specification		Spectrum Analyzer Specification		Impedance Analyzer Specification[2]	
Frequency Range	10Hz to 500MHz[1]	Frequency Range	10Hz to 500MHz	Frequency Range	100kHz to 500MHz
Frequency Resolution	1mHz	Noise Sidebands	< -104dBc/Hz typical at 10kHz offset	Meas. Parameter	$|Z|$, θz, R, X, $|Y|$, θy, G, B, Cs, Cp, Ls, Lp, Rp,
Output Power Range	-50 to15dBm	Resolution Bandwidth	1Hz to 1MHz in 1-3-10 steps		Rs, X, D, Q, $|\Gamma|$, Γx, Γy
				Z Accuracy	3% (typical, basic accuracy)
Dynamic Range	115dB@10Hz IFBW	Dynamic Range	> 100dB third-order free dynamic range	Source Level	-56dBm to +9dBm(at DUT)
				DC Bias	40 V (20 mA(max))
Dynamic Accuracy	0.05dB/0.3deg.	Level Accuracy	0.8dB@50MHz		(Opt.001 DC source or
Calibration	full two-port	Sensitivity	-145dBm/Hz		External DC source is
			@freq. = 10MHz		required.)
				Compensation	OPEN/SHORT/LOAD
					Port Extension

Standard Features	: Instrument BASIC, HP-IB port, 3.5" floppy disk drive, direct print, RAM disk, VGA Monitor Output
Optional Features	: Impedance measurement (opt. 010), Time-Gated spectrum Analysis (opt. 1D6), High-Stability Frequency Reference (opt. 1D5), 50Ω to 75Ω Spectrum Input Impedance Conversion (opt. 1D7), DC Source(> 40V, 100mA (ALC)) (opt.001)

1: 100kHz to 500MHz if using the HP 87511A/B S-parameter test set.
2: With Option 010 and the HP 43961A RF impedance test kit

Table 2. HP 4396B Major Specification

Network Analyzer Specification		Spectrum Analyzer Specification		Impedance Analyzer Specification[2]	
Frequency Range	100kHz to 1.8GHz[1]	Frequency Range	2Hz to 1.8GHz	Frequency Range	100kHz to 1.8GHz
Frequency Resolution	1mHz	Noise Sidebands	< -113dBc/Hz typical at 10kHz offset	Meas. Parameter	$|Z|$, θz, R, X, $|Y|$, θy, G, B,Cs, Cp, Ls, Lp, Rp,
Output Power Range	-60 to 20dBm	Resolution Bandwidth	1Hz to 3MHz in 1-3-10 steps		Rs, X,D, Q, $|\Gamma|$, Γx, Γy
				Meas. range	2 Ω to 5 kΩ
Dynamic Range	> 120dB@10Hz IFBW	Dynamic Range	> 100dB third-order dynamic range	Z Accuracy	3% (typical, basic accuracy)
				Source Level	-66 dBm to +14 dBm
					(at DUT)
Dynamic Accuracy	0.05dB/0.3deg.	Overall Level Accuracy	< 1.0dB	DC Bias	40 V (20 mA(max))
Calibration	full two-port	Sensitivity	< -147dBm/Hz @freq. = 1GHz		(External DC bias source is required.)
				Compensation	OPEN/SHORT/LOAD Port Extension

Standard Features	: Instrument BASIC, HP-IB port, 3.5" floppy disk drive, direct print, RAM disk, VGA Monitor Output
Optional Features	: Impedance measurement (opt. 010), Time-Gated spectrum Analysis (opt. 1D6), High-Stability Frequency Reference (opt. 1D5), 50Ω to 75Ω Spectrum Input Impedance Conversion (opt. 1D7)

1: 300kHz to 1.8GHz if using the HP 85046A/B S-parameter test set.
2: With Option 010 and the HP 43961A RF impedance test kit

HP Combination Analyzer Family Measurement Examples

The HP Combination Analyzer Family is a powerful tool for effective evaluation of electronic circuit and device performance. The following shows you some measurement examples by the HP combination analyzers.

Amplifier Evaluation

Amplifier characterization requires the evaluation of a variety of measurement parameters via vector network analysis as well as spectrum analysis. Figure 2 shows the major measurement parameters for amplifier evaluation.
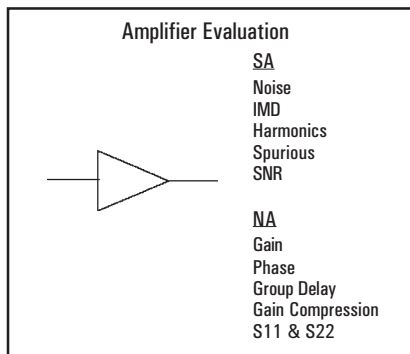

Figure 2. Major Measurement Parameters of Amplifier

Network Evaluation for Amplifier

The measurement configuration for network analysis of an amplifier is shown in Figure 3. Either an optional Reflection/Transmission test set or an optional S-parameter test set is required to perform this analysis.
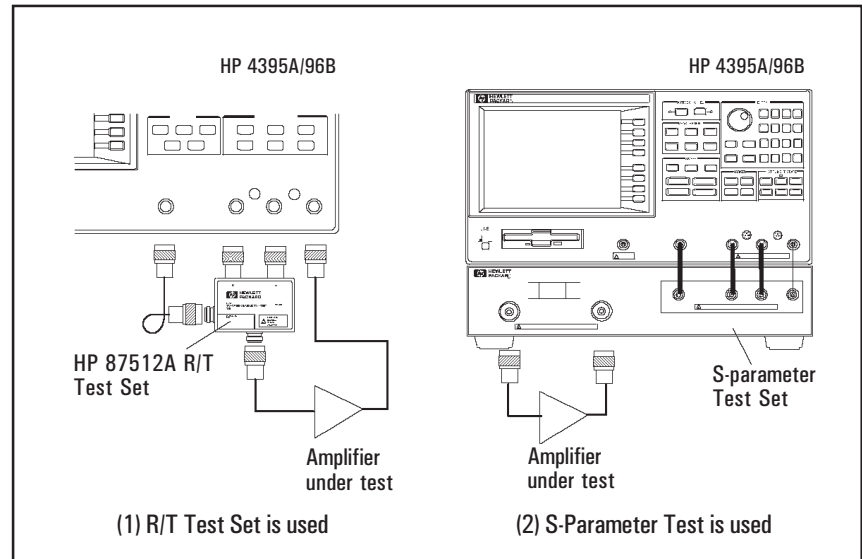

Figure 3. Measurement Configuration for Amplifier Network Analysis.

Figure 4. Gain/Phase of the Amplifier

• Gain and Phase Measurement

The amplifier gain is defined as the ratio of the amplifier output power (delivered to a Z_0 load) to the input power (delivered from a Z_0 source), where (Z_0) is the characteristic impedance of the system. The Amplifier gain is most commonly specified as a typical or minimum value over a specified frequency range, while assuming that input and output signals are in the amplifier's linear operating range. Figure 4 shows the gain and phase measurement result of an amplifier.

• **Gain Compression Measurement**

The amplifier gain at a single frequency is based on ideally linear performance between the input power and the output power. The real amplifier gain is nonlinear. The output power becomes saturated even if the input power is increased. The most common measurement of amplifier compression is the 1-dB compression point. This is defined as the input power which results in a 1-dB decrease in amplifier gain. The easiest way to measure the 1-dB compression point is to directly display normalized gain (ratio between the reference channel and the test channel).

Figure 5 shows the gain compression measurement result (normalized gain). The flat part of the trace is linear, and the curved part (of the right side) corresponds to compression caused by higher input power. The HP Combination Analyzers have the ability to do power sweeps where the maximum range is 20 dB. The marker function can easily indicate the 1-dB decrease point. These functions help you to evaluate the gain compression of the amplifier easily.

Figure 5. Gain Compression of Amplifier

• **Return Loss (S_{11}, S_{22}) Measurement**

When S_{11}, S_{22}, or Return loss are measured, either the Reflection/Transmission Test Set or the S-Parameter test set is required (as shown in Figure 3).

The input and output in a high frequency circuit are matched with a characteristic impedance, which may drift from the ideal characteristic impedance depending on frequency. This change in characteristic impedance will cause reflections. The indicated reflection parameters are the reflection coefficient (Gamma (S_{11} or S_{22})) and return loss(Rl). The return loss is calculated by using the following formula.

$$Rl = -20 \times \log(S_{11}) \text{ or } -20 \times \log(S_{22})$$

When the input and the output are perfectly matched, there is no reflection which means Rl is minus infinity. Figure 6 shows the return loss measurement result example for an amplifier.

In case of using the S-parameter test set with the instrument, you can perform the full two port calibration to obtain the best accuracy for the input or output impedance and the other evaluations.
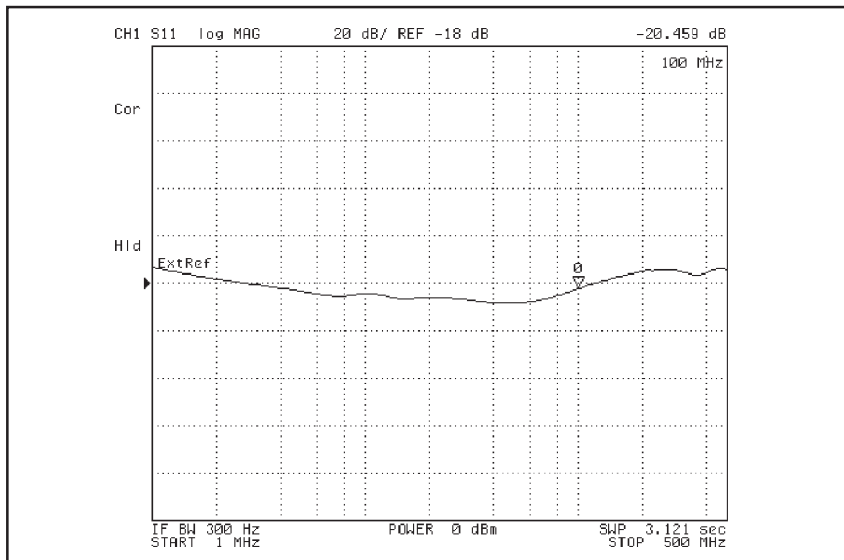

Figure 6. Return Loss Measurement Example

Spectrum Evaluation for Amplifier

- **Harmonic Distortion Measurement**

Nonlinear behaviors in the amplifier will cause harmonics of the input signal to appear at the output along with the fundamental. These harmonics are integer multiples of the input (fundamental) frequency, and are usually specified in terms of dB below the fundamental signal for a given input level (commonly expressed as dBc). The measurement configuration for the harmonic distortion is shown in Figure 7.
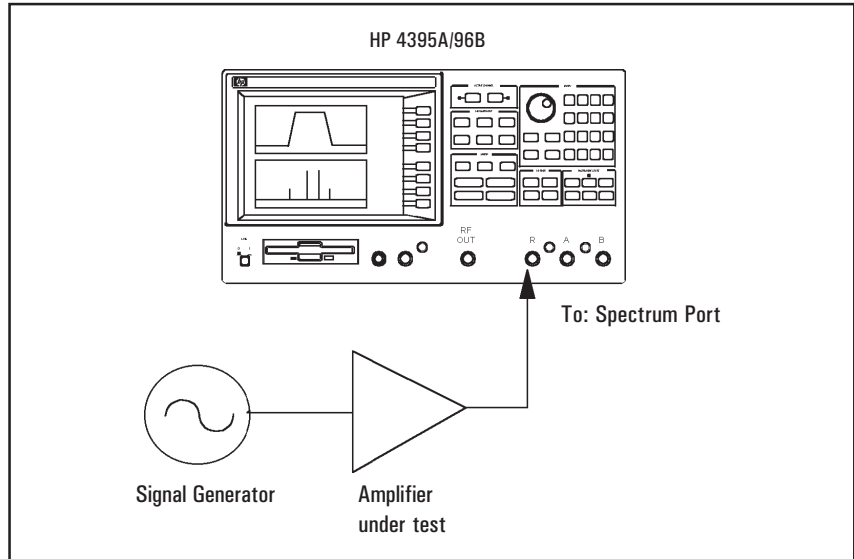

Figure 7. Measurement Configuration for Harmonic Distortion
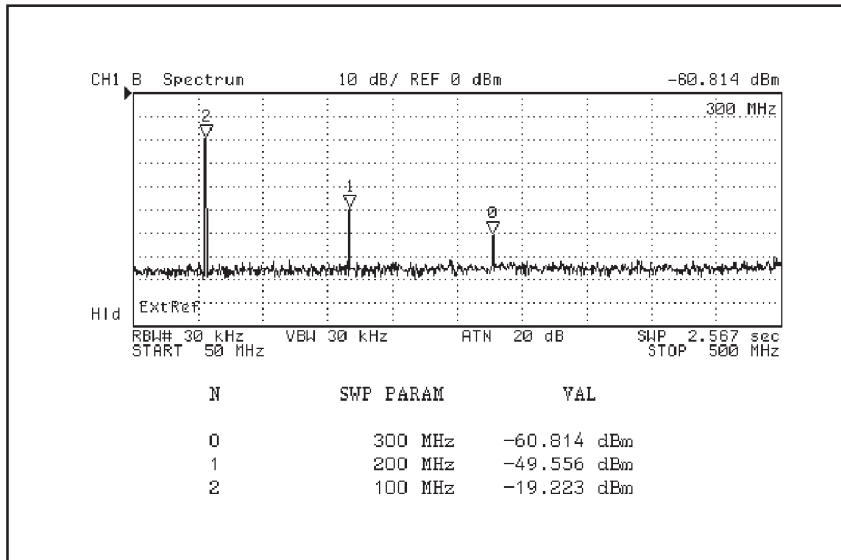
Figure 8. Harmonic Distortion Measurement

The HP 4395A/96B has a multiple marker function. This function can easily indicate all of the harmonic distortion points. Figure 8 shows the measurement example for harmonic distortion of an amplifier.

• **Intermodulation Distortion Measurement**

Another nonlinear behavior in amplifiers is intermodulation distortion. When two input signals are applied to a nonlinear amplifier, the output contains additional frequency components. These additional components are the intermodulation distortion products. As products of a two-tone example, the output signal will contain frequency components at the two fundamental input frequencies [f_1 and f_2], harmonics will be seen at [$2 \times f_1$, $2 \times f_2$, $3 \times f_1$, and $3 \times f_2$], second-order products at [$f_1 + f_2$ and $f_1 - f_2$], and third order products at [$2 \times f_1 - f_2$ and $2 \times f_2 - f_1$]. The third order products are very close to the fundamentals and typically fall within the bandwidth of the amplifier. To measure intermodulation distortion, two signal generators are required. The signal generators outputs are connected together through a coupler or combiner. This device must ensure sufficient isolation between the two RF sources so that no intermodulation occurs in their output stages. The measurement configuration is shown in Figure 9.
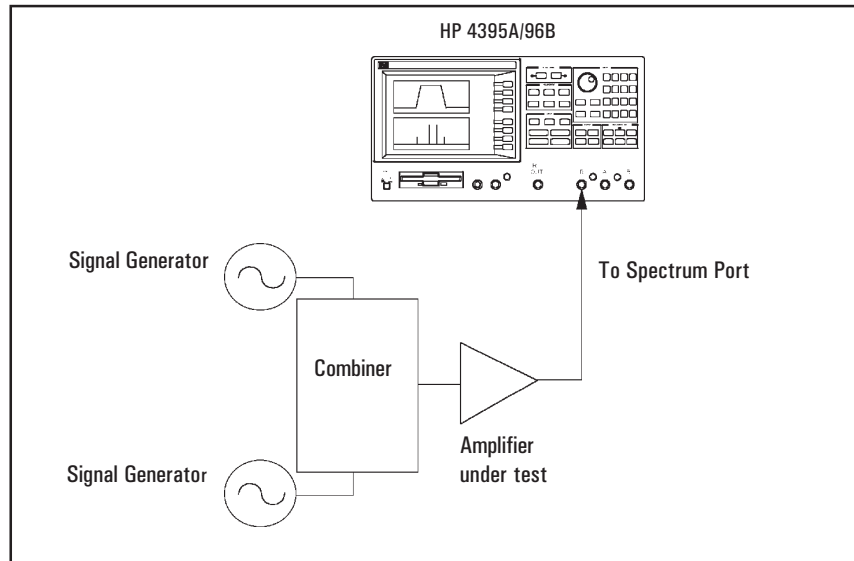

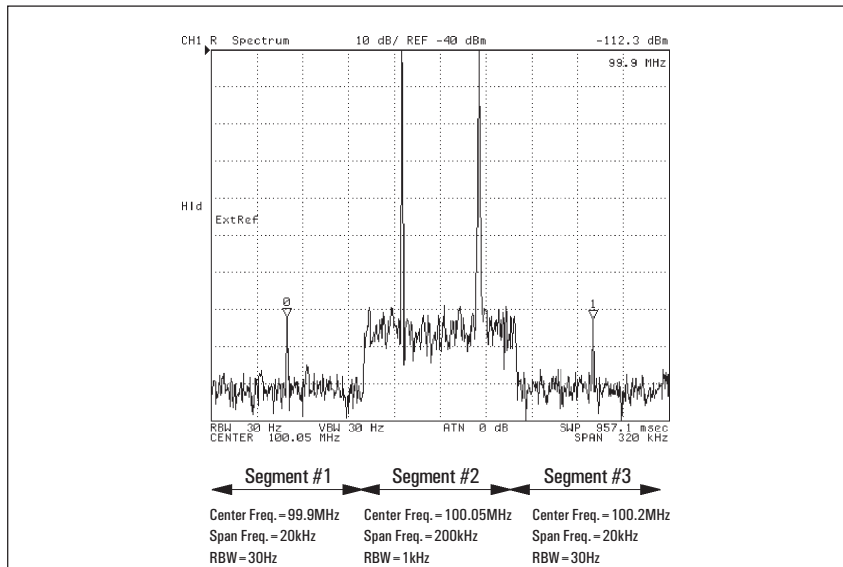**Figure 9. Measurement Configuration of the Intermodulation Distortion**

Figure 10. Measurement Results of Intermodulation Distortion by Using List Sweep Function

The HP 4395A/96B, using the list sweep function, allows you to break the span into segments with variable numbers of points and RBW's. This optimizes the sweep speed for proper dynamic range, and enables you to look at both the two tone signals and the intermodulation distortions. Figure 10 shows the measurement results by using the list sweep function.

• Noise Figure (NF) Measurement

Noise Figure (NF) expresses the degree of noise generated in an amplifier. The NF value for an ideal amplifier, with zero internal noise, is 1 (=0dB). The NF value for an amplifier is determined with the following formula.

$$NF = \frac{Cin/Nin}{Cout/Nout} = \frac{Cin/kTB}{CinG/Nout} = \frac{Nout}{GKTB}$$

Where,
Cin = Input Signal Power [W]
Nin = Input Signal Power [W]
Cout = Output Signal Power [W]
Nout = Output Noise Power [W]
K = Bolzmann's constant = 1.281×10^{-13} (J/°K)
T = Absolute Temperature (°K)
B = Noise Bandwidth (Hz)
G = Amplifier Gain

The NF value can be displayed on the log scale by using the following formula.

$$NF \ [dB] = 10 \log \frac{Nout}{GKTB}$$
$$= 10 \log \frac{Nout}{B} - 10 \log G - 10 \log (KT)$$

The third item is a constant which becomes 10 log (KT) = -174 dBm/Hz when the temperature is 23 degree C. Thus, only the first item (i.e. noise power) and the second item (i.e. an amplifier's gain) have to be measured. The formula for determining NF can be expressed as follows.

NF [dB] = Nout [dBm/Hz] - G [dB] + 174 [dBm/Hz]

N and G are the noise level and amplifier gain as measured by the HP combination analyzers. For example, when Nout = -140 dBm/Hz and G = 10 dB, NF is 24 dB. These calculations can be easily customized using the built-in HP IBASIC function.

Filter Evaluation

Filters are generally passive, linear, two-port devices that can most often be completely characterized using swept frequency transmission/ reflection techniques, and sometimes spectrum technique.

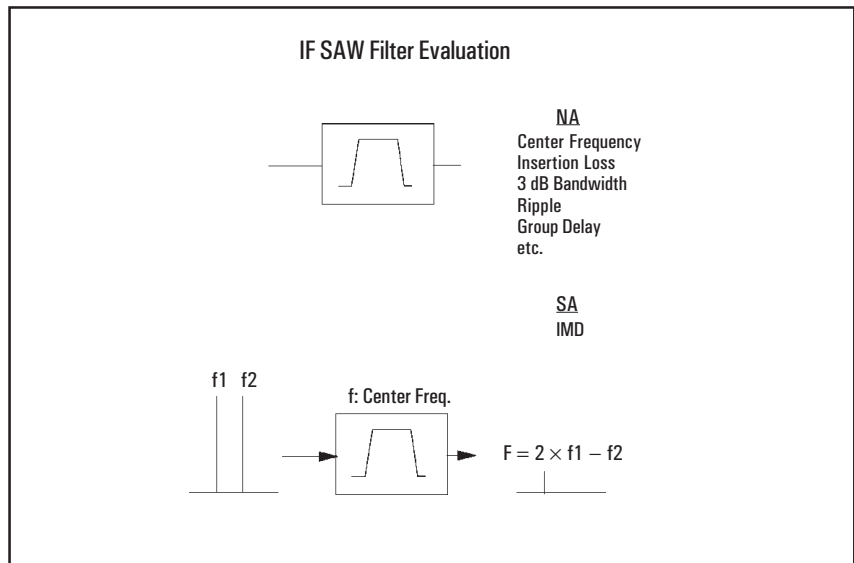Figure 11 shows the major measurement parameters for filter (especially IF SAW filter) evaluation.

IF SAW Filter Evaluation

NA
Center Frequency
Insertion Loss
3 dB Bandwidth
Ripple
Group Delay
etc.

SA
IMD

f1 f2   f: Center Freq.

$F = 2 \times f1 - f2$

Figure 11. Major Measurement Parameters of IF SAW Filter

Network Evaluation for Filter

The measurement configuration for network analysis of a filter is shown in Figure 12. Either an optional Reflection/Transmission test set or an optional S-parameter test set is required to perfrom this analysis.
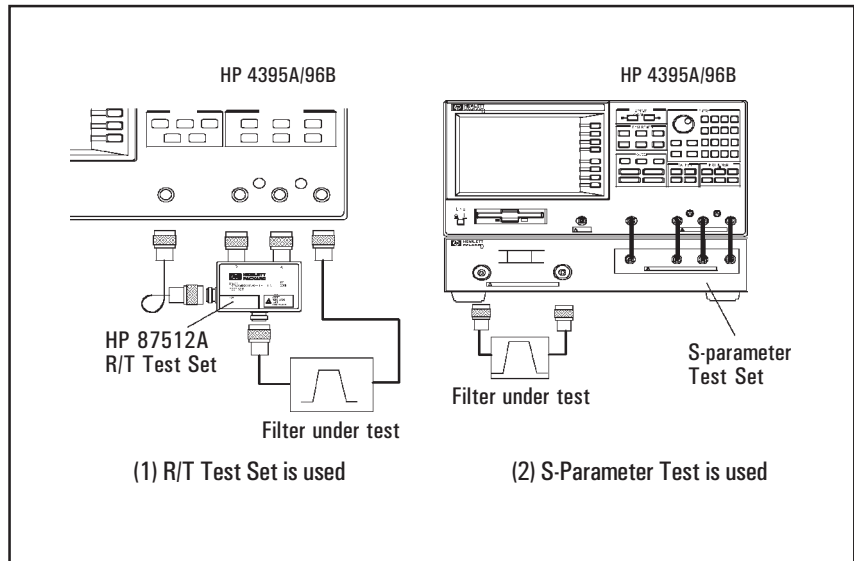

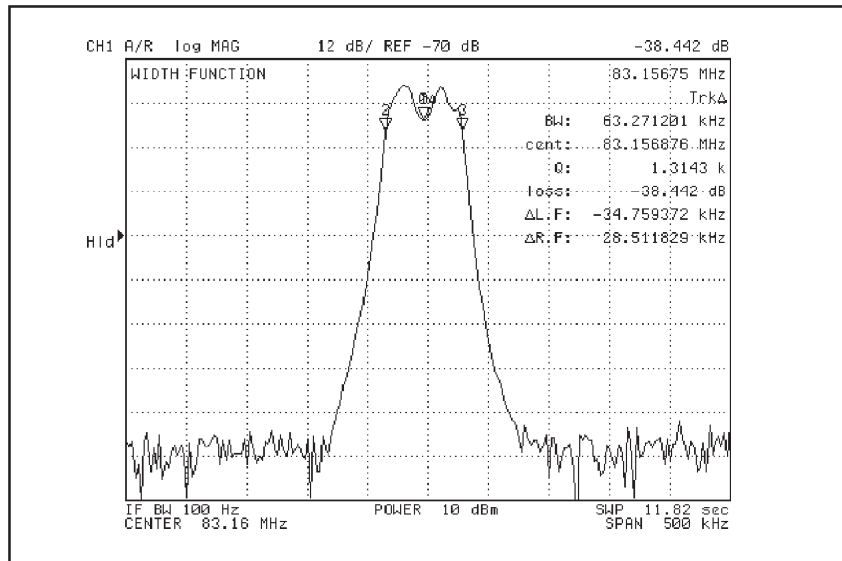Figure 12. Measurement Configuration for Filter Evaluation

Figure 13. Measurement Example by using the bandwidth search feature

• **Insertion Loss/Bandwidth Measurement**

Filters are required to pass signals falling within a specified bandwidth with minimum loss and distortion, while rejecting signals outside of that bandwidth. Insertion Loss is defined in dB as 20 times the log of the transmitted voltage divided by the incident voltages (All signals within the bandwidth will be attenuated identically).
Out-of-band rejection is a measure of how well a filter passes signals within its bandwidth while simultaneously rejecting all other signals outside of that same bandwidth. The HP 4395A/96B is suitable for this measurement due to wide dynamic range (≥115 dB).
The bandwidth search feature automatically calculates the center sweep parameter value, bandwidth, Q, insertion loss, cut-off point deviation (from the center of a bandpass or band reject trace). This feature also displays the calculation for all of these parameters. Figure 13 shows the measurement example using the bandwidth search feature.

• Group Delay Measurement

Recently, linear phase performance of a filter's bandwidth is quite important in digital communication. The linear phase performance (linearity of the device's phase vs. frequency) is evaluated using group delay as the measurement parameter. Group delay is a measure of the slope of the transmission phase response. The formula for the group delay is as follows:

Group Delay = - delta phase / (360 × delta freq.)

Where,
delta phase: phase difference between frequency apertures
delta freq.: frequency aperture

The frequency aperture (%) must be set for the proper group delay evaluation result.
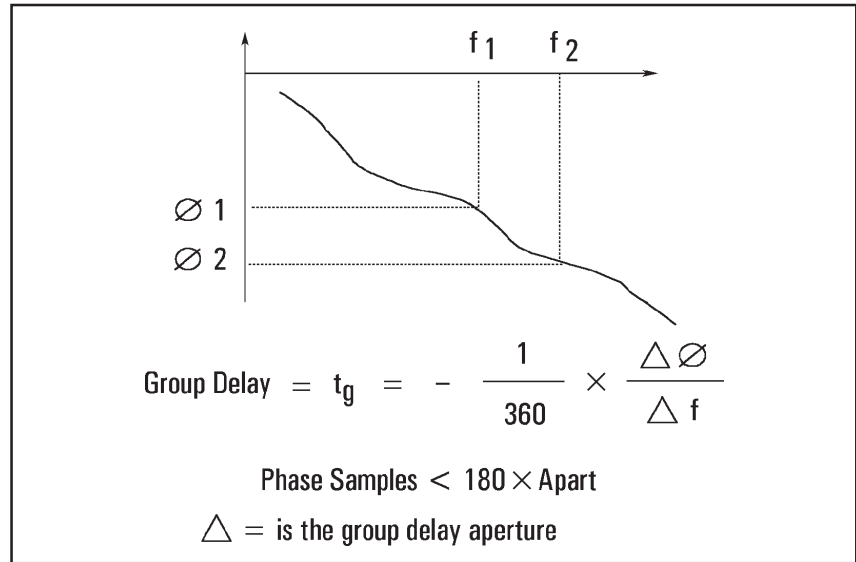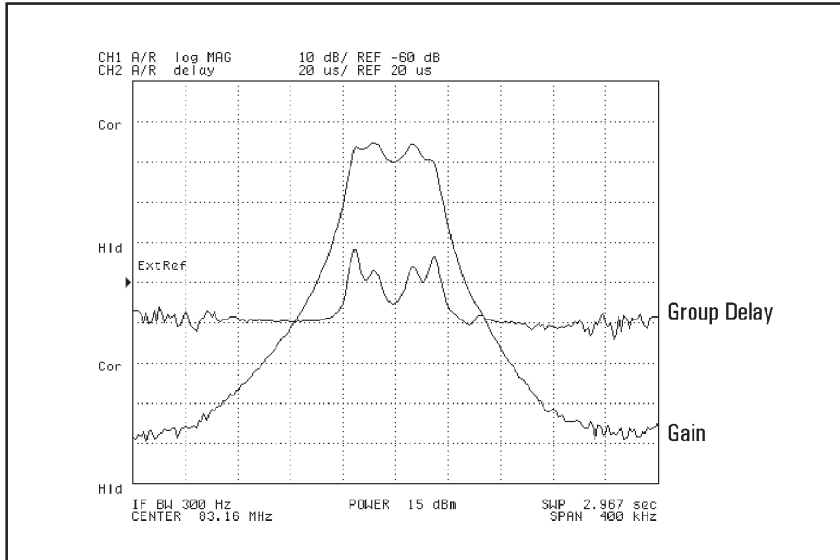

$$\text{Group Delay} \; = \; t_g \; = \; - \; \frac{1}{360} \; \times \; \frac{\triangle \varnothing}{\triangle f}$$

Phase Samples $< 180 \times$ Apart

$\triangle$ = is the group delay aperture

Figure 14. Group Delay

Figure 15. Group Delay Measurement Result

Figure 15 shows the measurement results of group delay.

Spectrum Evaluation for Filter

• **Intermodulation Distortion Measurement**

Intermediate Frequency (IF) SAW filter evaluations require not only the general network filter parameter evaluation, but also intermodulation distortion evaluation. This measurement is performed by applying two input signals to a filter. A third order signal can then be seen within the filter bandwidth. For example, when the center frequency of the filter is f_0, and the two input signals are $f_1 = f_0 + 100$ kHz, $f_2 = f_0 + 200$ kHz, the third order signal $((2 \times f_1 - f_2) = f_0)$ inputs to the filter. The size of this third order signal can be evaluated after going through the filter using the spectrum analyzer. The measurement configuration for the SAW filter intermodulation distortion is shown in Figure 16.
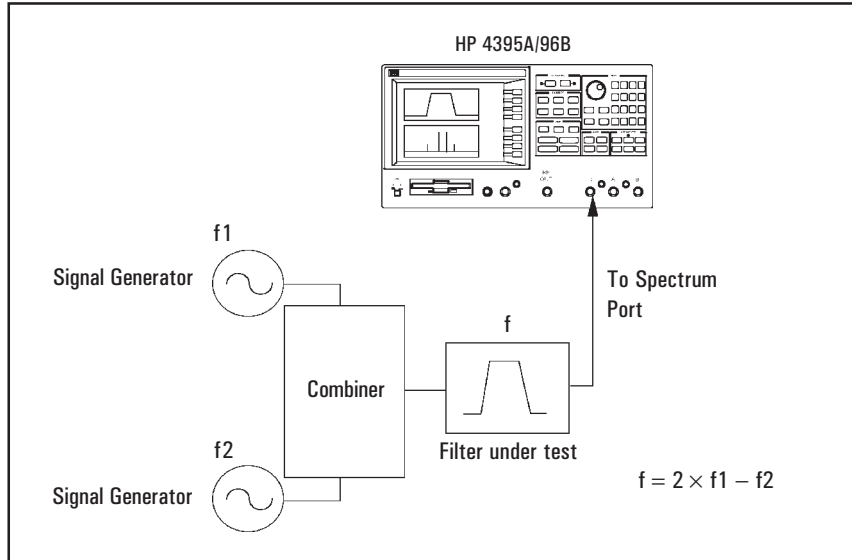

Figure 16. Measurement Configuration of the SAW Filter Intermodulation Distortion
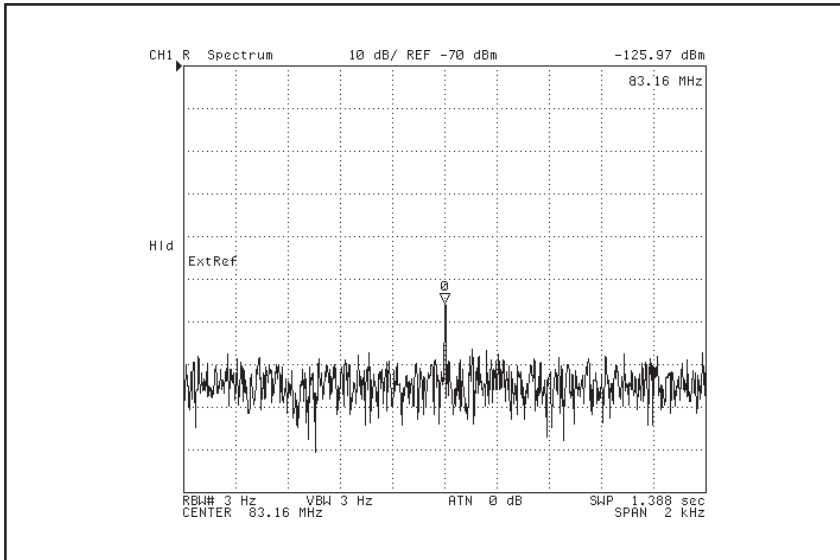

Figure 17. IMD measurement of SAW filter

Figure 17 shows the 83.16 MHz SAW filter intermodulation distortion measurement, with two input signals (83.16 MHz + 100 kHz, 83.16 MHz + 200 kHz).

As described before, the HP 4395A/96B are capable of both the vector network analysis and the spectrum analysis. These abilities contribute to savings in equipment cost, bench space, and work when performing filter evaluations.

Capacitor Evaluation

It is important to evaluate electronic devices at the actual operating condition before performing circuit design. A full-featured impedance measurement function can be added to the HP 4395A/96B by adding Option 010 and the HP 43961A RF Impedance Test Kit. The HP 4395A impedance measurement system covers from 100 kHz to 500 MHz, while the HP 4396B impedance measurement system covers from 100 kHz to 1.8 GHz. The impedance measurement system configuration is shown in Figure 18. A variety of APC-7 type HP test fixtures can be used.
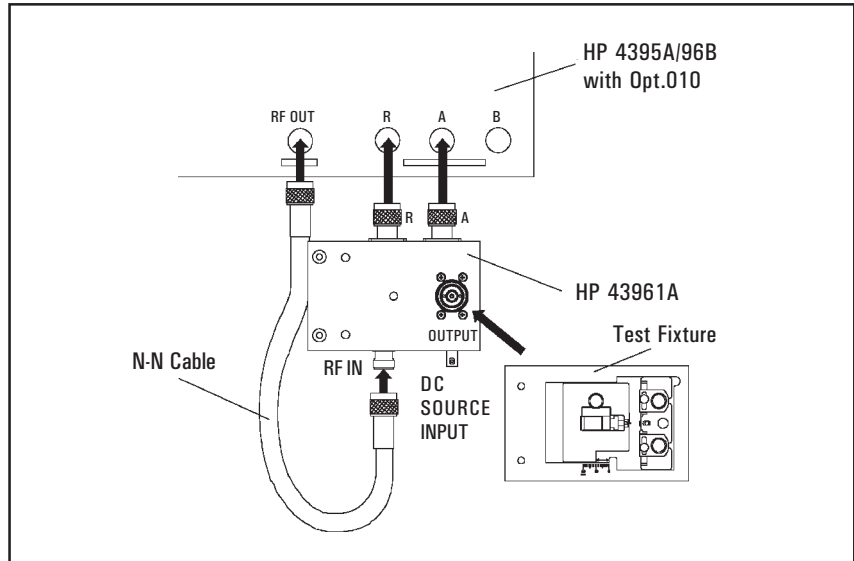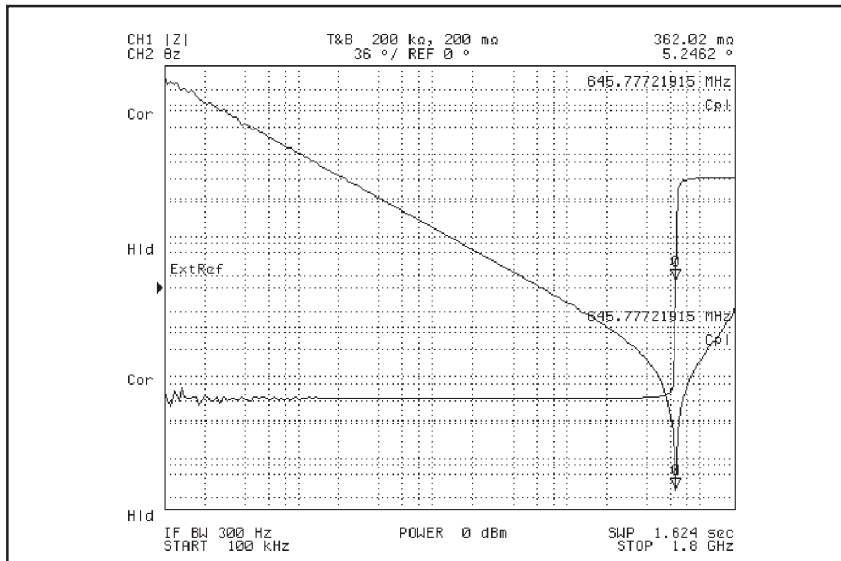

Figure 18. Impedance Measurement Configuration

Figure 19. Impedance Measurement Result of Capacitor

• **Direct Impedance Measurement**

The impedance measurement system provides accurate impedance measurement with direct impedance parameter read-out. To achieve accurate impedance measurement, these systems offer OPEN/SHORT/ LOAD and electrical delay compensation functions, which eliminate errors introduced by a test fixture. Figure 19 shows the impedance measurement results for a capacitor using the impedance measurement system.

• Equivalent Circuit Analysis

The impedance measurement function of the HP Combination Analyzer Family provides equivalent circuit analysis capability based on a three- or four-element circuit (Figure 20). This feature allows Calculation of the impedance parameters for each equivalent circuit element, and will also simulate the frequency characteristics based on the calculated parameters.
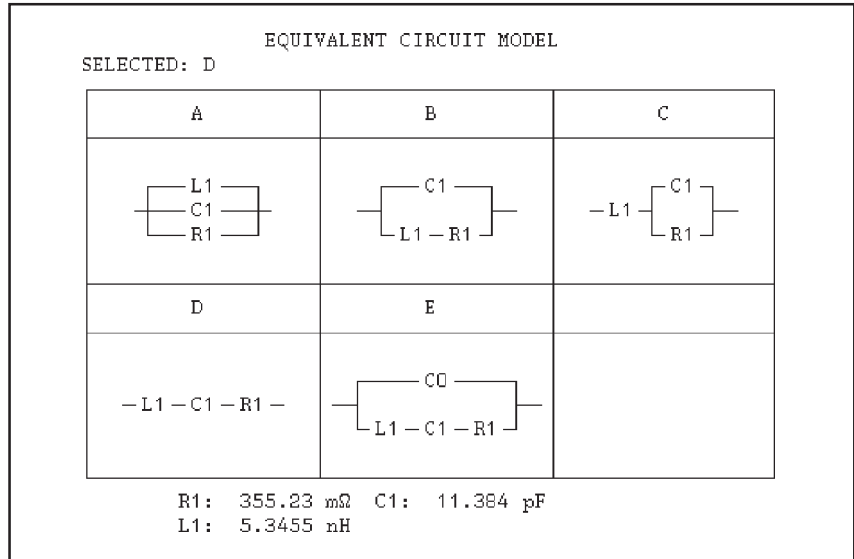

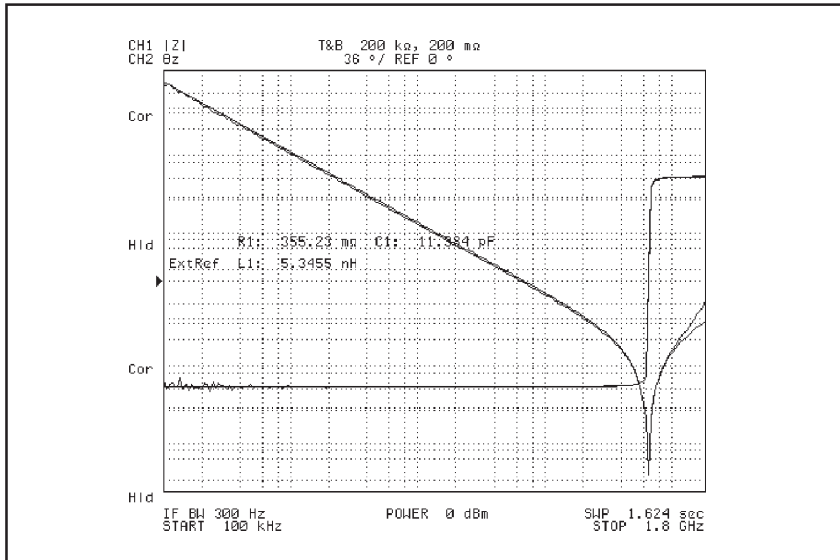**Figure 20. Five Equivalent Circuit Models**

Figure 21. Simulation of Frequency Characteristics

Figure 21 shows a comparison between an actual measurement result and the simulated result. You can see the simulated characteristics are almost the same as the actual characteristics.

Conclusion

The HP Combination Analyzers keeps up with your demands by offering the capabilities you need for your product's development.

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Canada:
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Mississauga, Ontario
L4W 5G1
(905) 206 4725

Europe:
Hewlett-Packard
European Marketing Centre
P.O. Box 999
1180 AZ Amstelveen
The Netherlands
(31 20) 547 9900

Japan:
Hewlett-Packard Japan Ltd.
Measurement Assistance Center
9-1, Takakura-Cho, Hachioji-Shi,
Tokyo 192, Japan
Tel: (81) 426 56 7832
Fax: (81) 426 56 7840

Latin America:
Hewlett-Packard
Latin American Region Headquarters
5200 Blue Lagoon Drive
9th Floor
Miami, Florida 33126
U.S.A.
Tel: (305) 267-4245
     (305) 267-4220
Fax: (305) 267-4288

Australia/New Zealand:
Hewlett-Packard Australia Ltd.
31-41 Joseph Street
Blackburn, Victoria 3130
Australia
Tel: 1 800 629 485 (Australia)
     0800 738 378 (New Zealand)
Fax: (61 3) 9210 5489

Asia Pacific:
Hewlett-Packard Asia Pacific Ltd.
17-21/F Shell Tower, Times Square,
1 Matheson Street, Causeway Bay,
Hong Kong
Tel: (852) 2599 7777
Fax: (852) 2506 9285