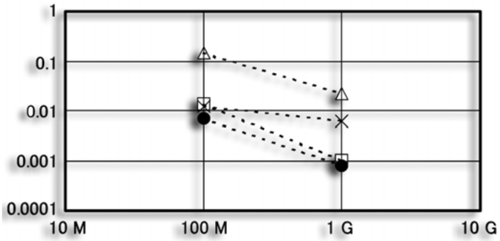
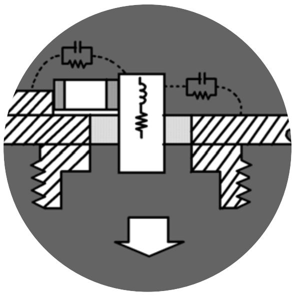
Agilent
Advanced impedance measurement capability of the RF I-V method compared to the network analysis method

Application Note 1369-2





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1. Introduction

Explosive demand for the electronic devices used in cellular phones and high-speed telecommunication equipment has increased the need for impedance characterization and analysis of these devices in the RF to microwave region. In the areas of passive device development, precise RF impedance measurement is vital for the evaluation of real device characteristics and problem analysis. In the RF circuit design environment, RF impedance measurement also aides high-performance circuit design by allowing accurate circuit simulation and selection of appropriate devices for the designed circuit.

Accurate, easy to perform impedance measurements are required to evaluate RF characteristics of generic passive components, such as capacitors, inductors, diodes, PC board patterns etc., because the frequency dependence of these devices are not necessarily found in their catalog specifications. Actual impedance characteristics of these devices will influence the circuit's operating performance. RF impedance characterization allows the circuits to be designed using the device data at the frequencies at which the devices are actually used.

There are several techniques to choose from in making RF impedance measurements, as shown in figure 1. Each technique has advantages and disadvantages: The reflection coefficient, transmission, and S-parameter measurement methods are conventionally performed with network analyzers for impedance analysis in the MHz to GHz region. Pi (π) network method is the standard method for measuring impedance of quartz crystal resonators by means of transmission measurement at frequencies typically below 300 MHz. The RF I-V method, which is incorporated in the current RF impedance analyzers, is an advanced measurement technique to perform accurate one-port impedance measurements. In the frequency range up to 3 GHz, this method has the advantages of higher accuracy and a wider impedance measurement range than has been achieved before with other methods. This product note highlights the RF I-V method and describes differences between the impedance analyzer and the network analyzer to help you choose the appropriate measurement method for your intended application.

Note: This application note treats the one-port and two-port measurement methods for a two-terminal impedance element (device). The transfer impedance measurement of a multi-terminal circuit network (device with three or more terminals) is not treated because it can be made by the two-port measurement method only and is not an application that the impedance analyzers address. The measurement categories covered by this application note are illustrated in figure 2 below:

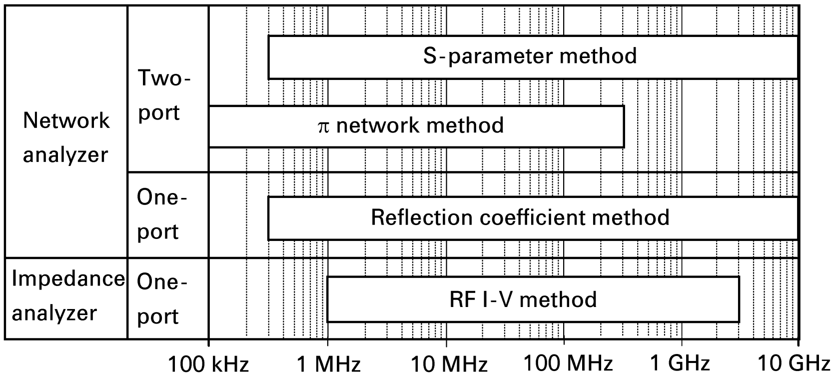


Figure 1. Typical frequency range of RF impedance measurement methods

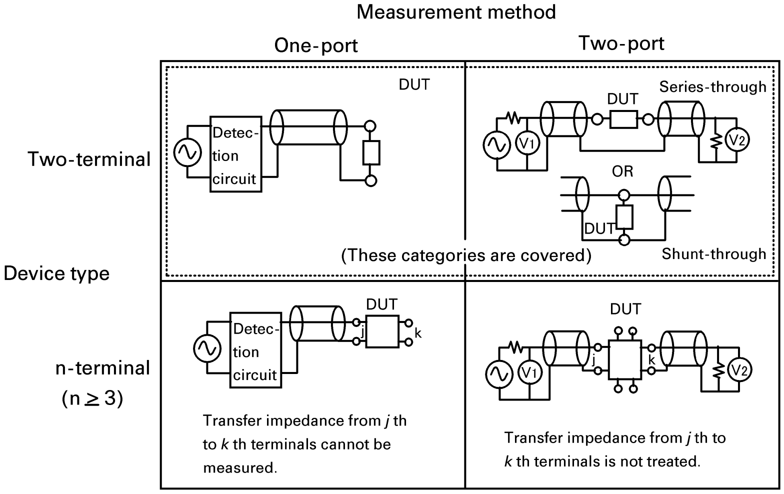


Figure 2. Categories of device types and measurement methods

2. Measurement application criteria

In comparing impedance analyzer and network analyzer, this section discusses how their application criteria and solutions to measurement needs are different from each other. The impedance measurement capabilities required for satisfying the device measurement needs are also clarified through the following discussion.

The impedance analyzer basically measures two-terminal devices such as capacitors, inductors, diodes, resonators, etc.. Measuring impedance reveals two key characteristics of the devices: loss factor (dissipation factor or Q factor) in the required frequency range and the frequency dependence of device parameters of interest, both of which result from inner parasitic parameters of the devices. The dissipation factor (= R/X) represents the relative magnitude of the parasitic resistance to the reactance of device. The lower the dissipation factor is, the more ideally reactive the device is.

Measuring a small resistive component separately from a greater reactive component of impedance requires a high accuracy for impedance phase angle. The frequency dependence of device parameters (C, L, R, |Z|, etc.) is caused by parasitic reactance elements in the device. The lower the parasitic parameter values are, the less frequency dependence (flat or monotonous characteristics over a wide frequency range) the device has. Therefore, for better frequency characteristics of impedance, the parasitics of the devices should be minimized as much as possible. The instrument must be able to accurately distinguish even small differences in the parasitic parameters. (This is also key factor for the evaluation of dielectric and magnetic materials used in electronic devices.) Accurate measurement of the parasitics enables equivalent circuit parameters of the devices to be derived.

Required performance to achieve accurate impedance characterization

To achieve accurate measurement for the small loss factors and parasitics, the following performance criteria must be achieved:

1. Accurate measurements of low D (high Q) and low ESR.
2. A wide impedance measurement range.
3. Excellent measurement stability after calibration.
4. Calibration and compensation functions to eliminate the error sources in the measurement circuit. Specifically, test fixture residuals (residual impedance and stray admittance) need to be accurately eliminated.

Examples of parasitics in devices

Figure 3 shows an example of impedance - frequency characteristics of a 33 pF capacitor. The graph indicates a D value of 0.0071 at 200 MHz, which corresponds to equivalent series resistance (ESR) of 174 mΩ. The equivalent series inductance (ESL) of the capacitor is calculated to be 430 pH from the self-resonant frequency (SRF) of 1.336 GHz. Figure 4 shows characteristics of a 10 nH inductor. Q value at 1 GHz is 41.5, corresponding to ESR of 1.67 Ω. The equivalent parallel capacitance calculated from the SRF is 3.7 pF. Although the parasitics inherent in the devices are small values, they dominate the high frequency characteristics of the devices.

Let's examine the required accuracy in using the network analysis method to measure the 33 pF capacitor and the 10 nH inductor for the following conditions:

D value for 33 pF:
0.0071 ± 0.002
Q value for 10 nH:
41.5 ± 5

The required reflection coefficient and S21 accuracy is estimated as follows:

	33 pF @ 200 MHz	10 nH @ 1 GHz
|Γ|	± 0.0016	± 0.0027
S21	± 0.004 dB	± 0.012 dB

Note: S21 accuracy applies to series-through type of DUT connection method.

The estimated results for these methods require extremely high accuracy beyond the specified accuracy (|Γ| accuracy of ± 0.005 and S21 accuracy of ± 0.05 dB) of the highest performance class network analyzer. To measure the ESL of 430 pH at ± 20% accuracy, the uncertainty of the residual inductance involved between calibration plane and the device under test (DUT) must be within ± 86 pH. Accurate compensation for test fixture residuals is crucial for the measurement of such low ESL.

DUT's impedance will vary from low ohms to high kilo-ohms as shown in the capacitor and inductor measurement examples (figures 3 and 4). Therefore, it is required for the instrument to ensure the accuracy over a wide impedance measurement range.

A typical measurement routine will often take hours to complete, in cases where a lot of sample devices are measured for statistical analysis. The instrument must maintain accuracy continuously, to hold measurement consistency, against a lapse of time and variance in environmental temperature. The RF impedance analyzer addresses these measurement needs by providing vital solutions.

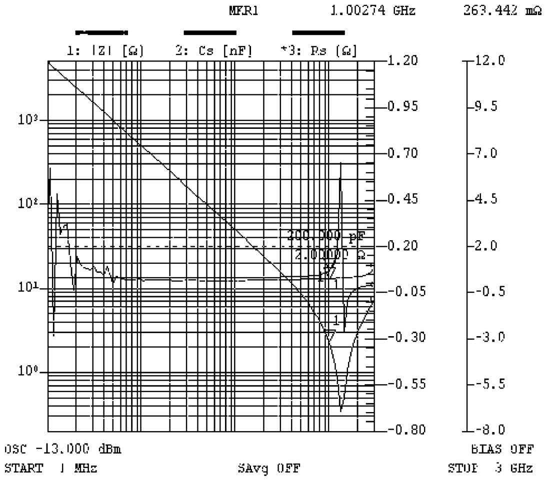


Figure 3. Frequency characteristics of a 33 pF capacitor

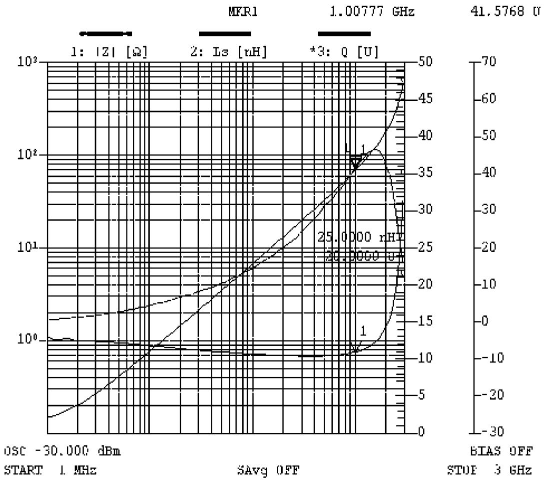


Figure 4. Frequency characteristics of a 10 nH inductor

3. Examination of measurement results

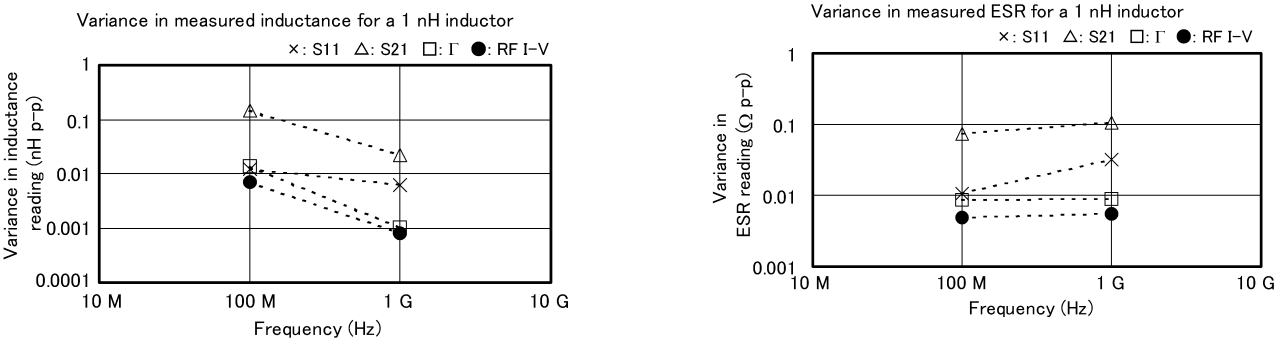
To realize the difference in practical measurement capabilities, let's examine the comparison results of measurements implemented for the RF impedance analyzer (RF I-V method) and the network analyzer. These measurements focus on measurement repeatability (short-term stability) and temperature dependence. The measurement accuracy is not highlighted because it depends on not only the accuracy of the instrument but also how the test-fixture-induced-errors could be eliminated. (In network analysis, calibration method at the tips of two-port test fixture greatly influences the measurement accuracy.)

Measurement repeatability test

Stability in repetitive measurements is a key performance required for accurately determining the loss factor and parasitics of the devices. The measurement stability test is performed using 1 pF and 33 pF capacitors and a 1 nH inductor at 100 MHz, 1 GHz and 3 GHz. These devices allow the test conditions to be set at low impedance, high impedance and nearly 50 Ω as shown in figure 7. Measurements are repeated 100 times continuously for each DUT at the specified test conditions, and the variance in measured values are plotted on the coordinates of the graphs shown in figures 5 and 6.

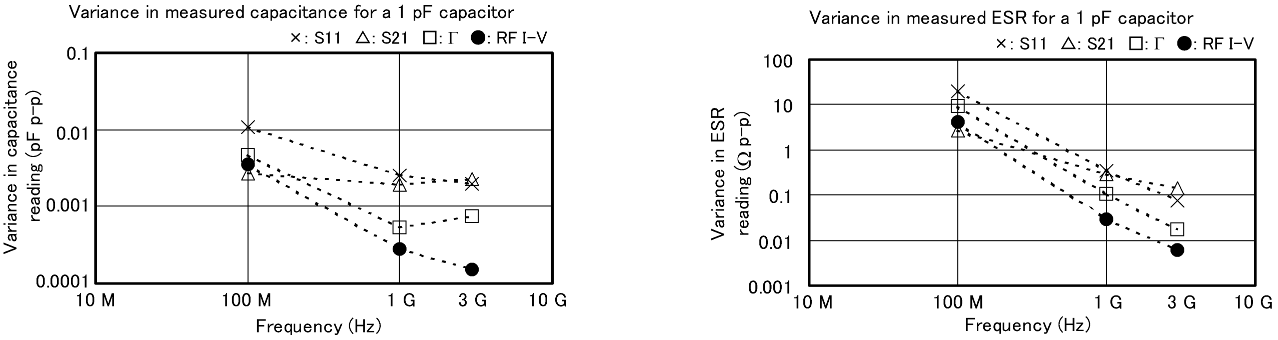
The test fixture keeps holding the DUT during the 100 measurements. Therefore, the test results manifest only the repeatability of the instrument and do not involve the test fixture's contact repeatability.

In comparing the variance in measured values of the RF I-V method to the other methods, the results of the RF I-V method demonstrate measurement repeatability (low variance) superior to the other methods in both low impedance and high impedance measurements.


Variance in measured inductance for a 1 nH inductor

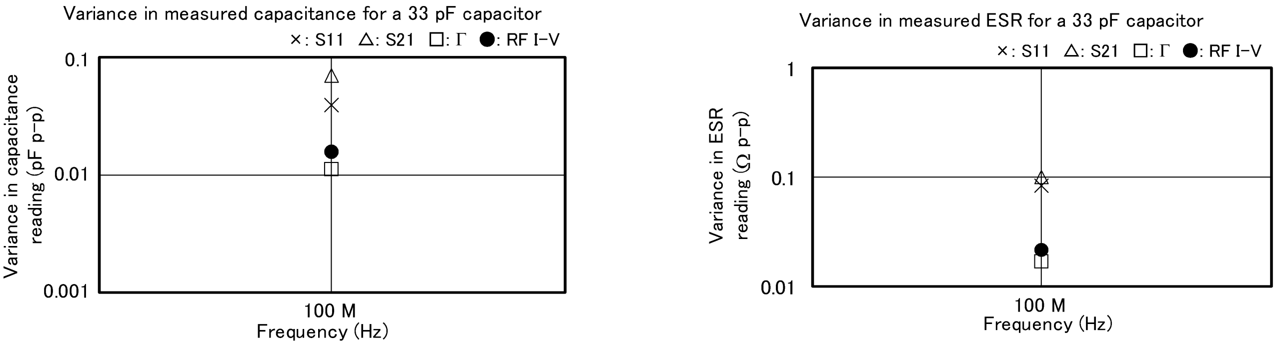
Variance in measured ESR for a 1 nH inductor

Note: These DUTs have low ESR values suited to test the stability in low loss measurements. In essence, the true ESR values of the DUTs need not be accurately known because the same DUTs (impedance) are measured by each measurement method. Actual ESR measurement values in each method do not coincide with the results of other methods. It is because the calibration methods, the test-fixtures used, and the compensation methods for test-fixture residuals and for test-port extension are different for each measurement method. However, the discrepancies in measured ESR values do not significantly influence the variance data compared, and are negligible for all. For a detailed discussion on this issue, refer to Appendix A at the end of this application note.


Variance in measured capacitance for a 1 pF capacitor

Variance in measured ESR for a 1 pF capacitor

Note: Γ, S11 and S21 data in the above graphs represent the variances in inductance and ESR values translated from one-port reflection coefficient (Γ) and two-port S11 and S21 measurement values, respectively. S11 and S21 measurements are made using the series-through type of DUT connection configuration.


Variance in measured capacitance for a 33 pF capacitor

Variance in measured ESR for a 33 pF capacitor

Figure 5. Measurement repeatability test result examples

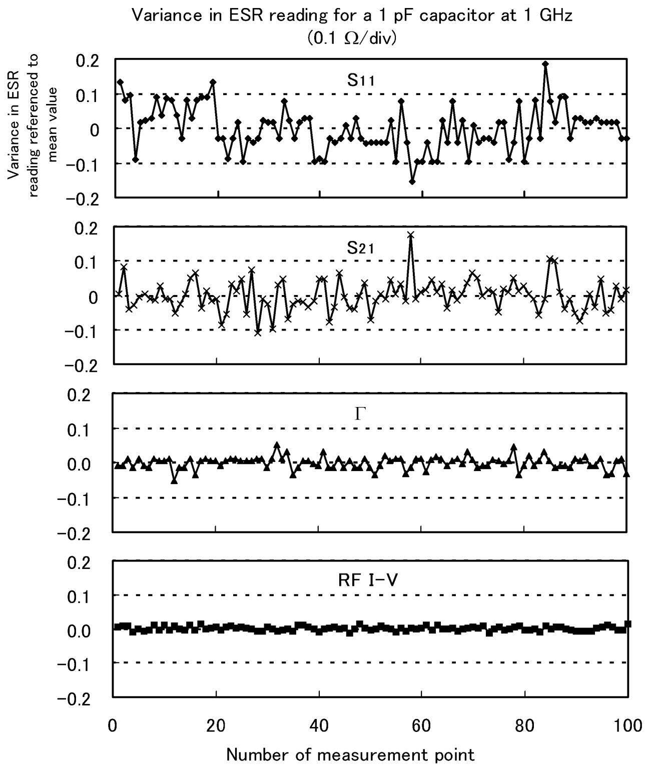


Figure 6. ESR measurement repeatability example for a 1 pF capacitor

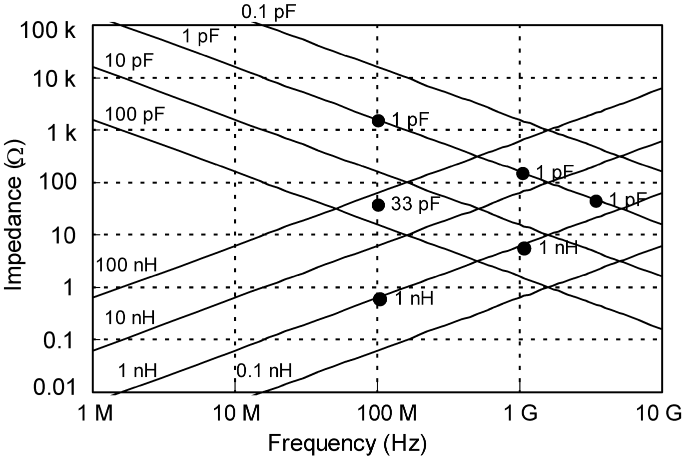


Figure 7. Sample device impedance and the measurement repeatability test conditions

Other test conditions:

Test level: 0 dBm
Measurement time: Approx.
  10 ms (RF I-V)
  Equivalently near 10 ms
  by averaging (Γ, S_{11} and S_{21})
IFBW (Γ, S_{11} and S_{21}): 100 Hz
Averaging: 1 (RF I-V)
  8 (Γ, S_{11} and S_{21})
Test fixture: 16196A
  (RF I-V and Γ)
  Micro strip-line fixture
  (S_{11} and S_{21})
DUT size: 1608 (mm code) /
  0603 (inch code)
Calibration: SOL (RF I-V)
  SOLT (Γ, S_{11} and S_{21})

Temperature dependence test

Figure 8 shows the temperature dependence test results at 100 MHz and 1 GHz for temperature settings of 18° C, 23° C and 28° C. The results of the RF I-V method exhibit stable measurements against the temperature changes regardless of the frequency and DUT's impedance.

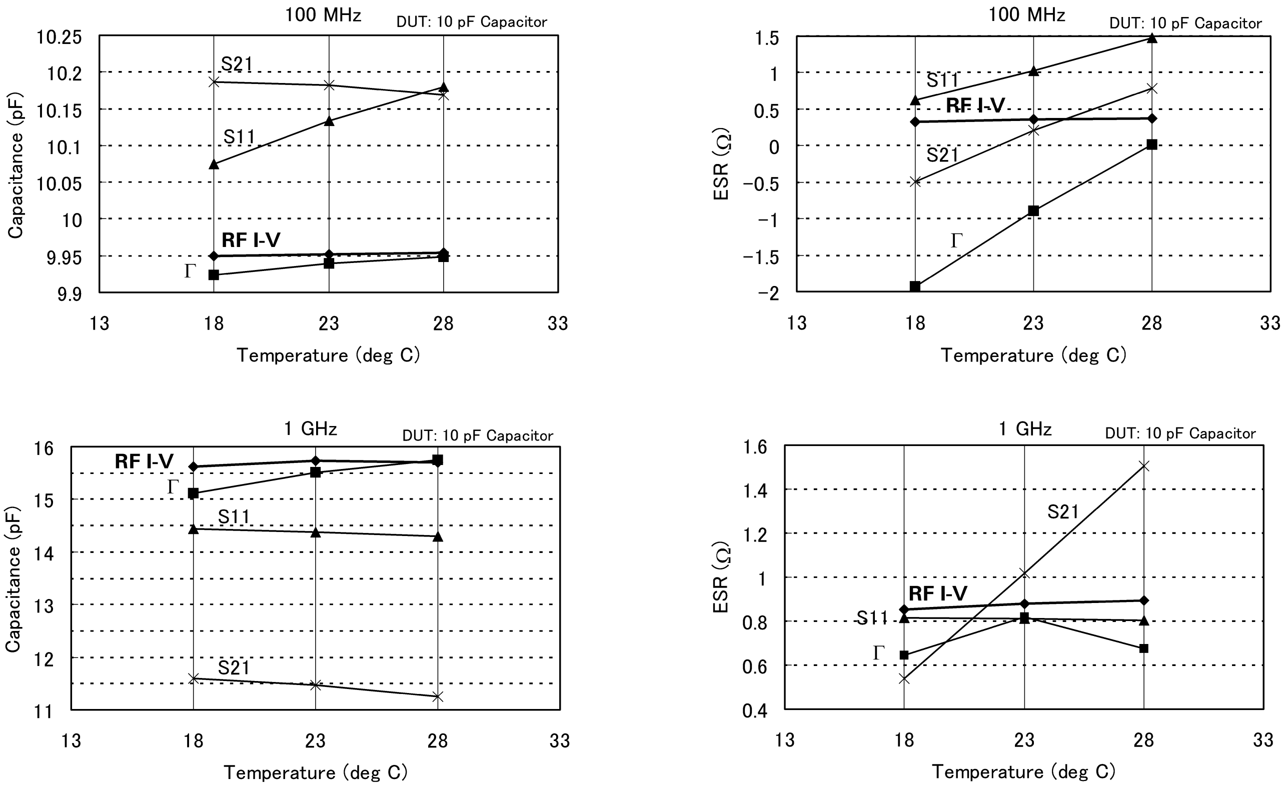


Figure 8. Temperature dependence test results example

Temperature dependence test conditions:

DUT: a 10 pF capacitor (Impedance: Approximately 160 Ω at 100 MHz and 16 Ω at 1 GHz)
Temperature coefficient of the DUT: < 30 ppm/ºC
Test level: 0 dBm
Calibration: SOL (RF I-V), SOLT (Γ, S11 and S21) at 25° C
DUT connection configuration for S11 and S21: series-through

Note: Γ, S11 and S21 graphs represent the capacitance and ESR values translated from one-port reflection coefficient (Γ) and two-port S11 and S21 measurement values, respectively. The RF I-V and Γ measurements are made using the same direct-attachment type coaxial test fixture (16196A). These measurement results directly represent the stability of the instruments.

The S11 and S21 are measured using two-port micro strip-line test fixture and test cables (indispensable for measurements). The S11 and S21 results are therefore influenced by the temperature characteristics of the test cable's propagation constant. This data exhibits possible temperature dependence of practical S-parameter measurements.

4. Measurement technique comparison

This section describes the technical concepts of the RF I-V method that deliver impedance measurement capabilities superior to the other techniques. Firstly, the reflection coefficient method is compared to the RF I-V method, and other methods are subsequently examined. Figure 9 shows the principle of each measurement method, the relationships of measured vector voltage ratio to impedance, and parameter calculation equations to derive impedance.

The reflection coefficient method measures the vector voltage ratio (Γ=Vr/Vi) of the incident signal and the reflected signal from the DUT. The relationship of voltage ratio to impedance is graphically shown in figure 9. The reflection coefficient in the graph assumes that the DUT is resistive. The logarithm of the detected voltage ratio is represented as return loss (= 20 log $|\Gamma|$). The reflection coefficient varies greatly with impedance, when the measured impedance Zx is near Zo (50 Ω). The highest accuracy is obtained at Zx equal to Zo, because the directional bridge (or coupler) for measuring reflection has a null balance point. The impedance measurement sensitivity degrades as the gradient of reflection coefficient curve levels off for both the lower and the higher impedance. The reflection coefficient measurement does not exhibit as high a peak sensitivity for capacitive and inductive DUTs because it does not have null balance point for reactive impedance.

Note: The solid curves (Rx) in the graphs of "Vector voltage ratio relationship to impedance" in figure 9 apply to resistive DUTs and the broken curves (Xx) apply to reactive DUTs. The graphs represent the absolute values of the vector voltage ratios. The voltage ratios differ for the DUT's reactance and resistance because the magnitudes of the vector ratios vary depending on the phase angle relationship between the DUT's impedance and the measurement circuit impedance, Zo, which is resistive. The reactive DUTs yield less voltage ratios than the resistive DUTs.

<table>
<tr><th>Measurement principle</th><th>Vector voltage ratio relationship to impedance</th><th>Parameter derivation calculation</th><th>Zr value</th></tr>
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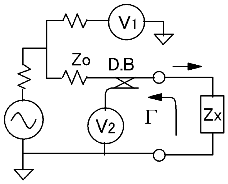
Reflection Γ



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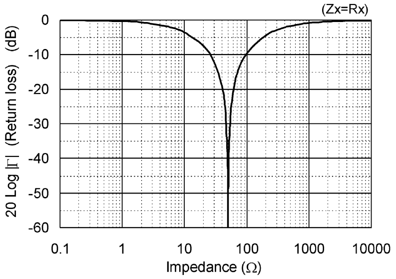

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$\Gamma = \frac{V2}{V1} = \frac{Zx - Zo}{Zx + Zo}$

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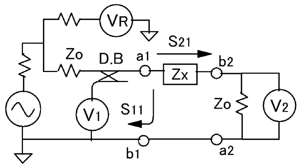
S-parameter S11, S21
Series-through mode



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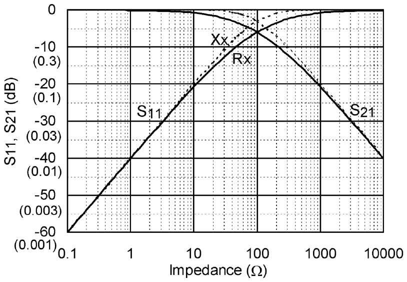

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$S11 = \frac{Zx}{Zx + 2Zo} = \frac{Zx}{Zx + 100}$

</td><td>100 Ω</td></tr>
<tr><td>

$S21 = \frac{1}{1 + \frac{Zx}{2Zo}} = \frac{100}{Zx + 100}$

</td><td>100 Ω</td></tr>
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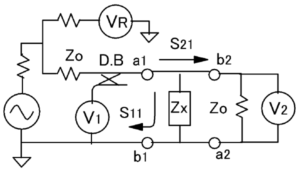
S-parameter S11, S21
Shunt-through mode



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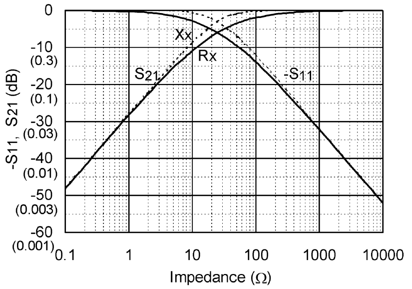

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$S11 = \frac{-Zo}{2Zx + Zo} = \frac{-25}{Zx + 25}$

</td><td>25 Ω</td></tr>
<tr><td>

$S21 = \frac{1}{1 + \frac{Zo}{2Zx}} = \frac{Zx}{Zx + 25}$

</td><td>25 Ω</td></tr>
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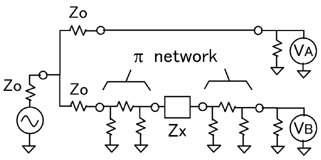
π network



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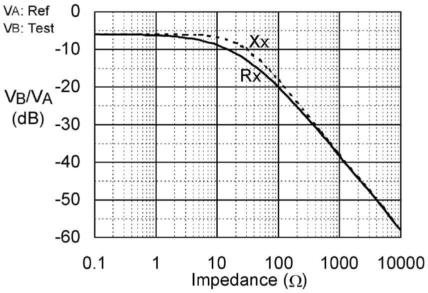

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$\frac{V_B}{V_A} = k\frac{12.4975}{24.995 + Zx}$

The graph is assumed that constant k is 1.

</td><td>25 Ω</td></tr>
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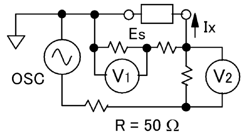
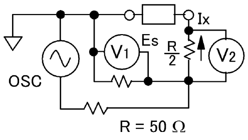
RF I-V

Low Z type



High Z type



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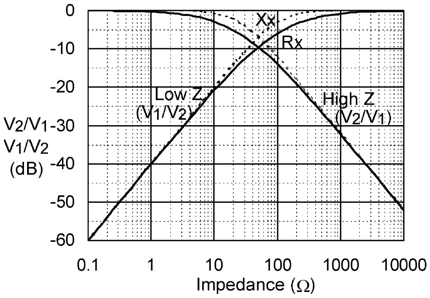

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Low Z type

$\frac{V1}{V2} = \frac{1}{1 + \frac{2R}{Zx}} = \frac{Zx}{Zx + 100}$

</td><td>100 Ω</td></tr>
<tr><td>

High Z type

$\frac{V2}{V1} = \frac{R}{2Zx + R} = \frac{25}{Zx + 25}$

</td><td>25 Ω</td></tr>
</table>

Figure 9. Measurement principles and vector voltage ratio relationships

Note: Zr is the roll-off impedance where the voltage ratio for the resistive DUT decreases by 6 dB and the voltage ratio for the reactive DUT decreases by 3 dB from the reference level (0 dB).

The RF I-V measurement method has two types of basic circuit (test head) configurations as illustrated in figure 9. The low impedance type configuration has a voltmeter near the DUT to accurately measure a low test voltage across a low impedance DUT. The high impedance type configuration has a current meter near the DUT to accurately measure a low test current through a high impedance DUT. The graph in Figure 9 shows the relationship of the measured vector voltage ratio to impedance for each type. The gradient of vector voltage ratio curve is constant (that is, the detected voltage ratio is proportional to impedance) over decades of impedance range and, as a result, constant measurement sensitivity is obtained. Though the measurement sensitivity degrades, as the gradient of vector voltage ratio levels off in the high impedance or low impedance regions, it is possible to selectively install the two types of test heads to complement the two measurement ranges.

Note: The Agilent E4991A employs a single test head capable of covering a wide impedance range without need of exchanging the test heads.

In S-parameter measurements, the DUT can be connected in series or shunt between the two test ports. The vector voltage ratios, detected in the S-parameter measurements, have relationships to impedance as shown in figure 9. These vector voltage ratio characteristics are similar to either the low impedance or high impedance type configurations of the RF I-V method. The difference between these measurement methods is found in the roll-off impedance, Zr, where the voltage ratio drops by 6 dB from the reference level (0 dB). The lower the Zr value is the better measurement sensitivity the high impedance type configuration has in the low impedance region. The higher the Zr value is the better measurement sensitivity the low impedance type has in the high impedance region, allowing a wider measurement coverage.

When the Zr values are compared, the RF I-V method has an advantage over the S21 measurement method in the impedance range where the sensitivity is nearly constant. S11 measurement and π network (transmission) methods are equivalent to the RF I-V method in terms of the Zr value. The S11 measurement, however, has a disadvantage in accuracy for low impedance and high impedance measurements because of calibration uncertainty. The measurement limits due to the calibration uncertainty is discussed in section 5.

The RF I-V circuit can be designed for Zr value that is properly shifted in order to extend the sensitive measurement range. The Agilent E4991A employs the single test head designed in this way, achieving a wide measurement range previously covered by combination of the high impedance and low impedance types. Figure 10 shows the vector voltage ratio characteristics of the E4991A.

Note: At a glance, the single test head configuration of the E4991A may seem to sacrifice a little the measurable impedance range when compared to the combined impedance range of the low impedance and high impedance type test heads. In practice, the E4991A's test head does not substantially carry such disadvantages, because the specified measurement range in high frequency region (above 10 MHz) is dominated by the calibration uncertainty as discussed in Section 7. The advanced design of the E4991A's test head ensures high SNR (signal-to-noise ratio) performance superior to the previous types of test heads.

The π network method allows constant test voltage to be applied to the device by decreasing the undesirable standing wave, which is caused by the reflected signal from the DUT. However, the maximum applied test level and SNR performance are degraded because π networks yield approximately 30 dB of insertion loss. This method is specifically used to measure quarts crystal resonators and is limited to a maximum frequency of 300 MHz.

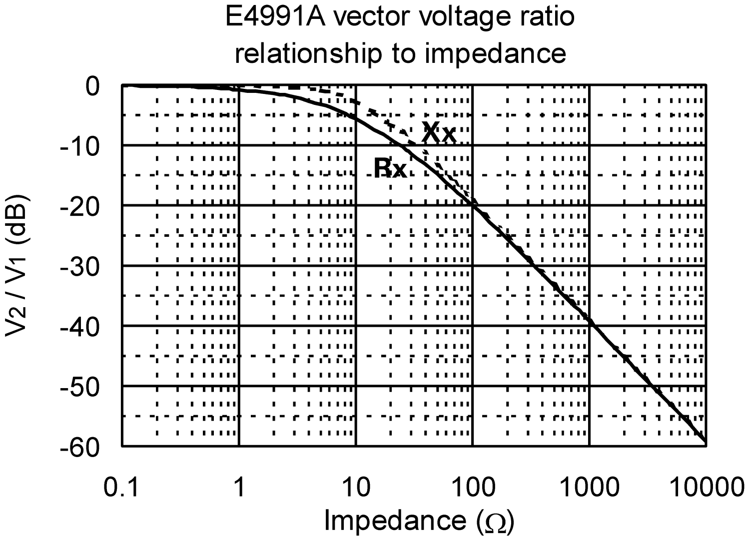


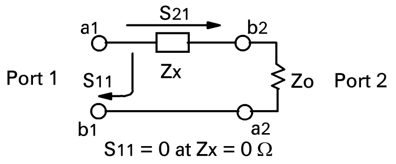
Figure 10. Vector voltage ratio characteristics of the E4991A

5. Influence of calibration uncertainties on impedance accuracy

Open, short and load calibration uncertainties affect the impedance measurement accuracy differently, depending on the measurement methods (principles.) When S_{11} is measured for a device connected in series between the test ports 1 and 2 as illustrated in figure 11 (a), S_{11} is zero for a DUT impedance of 0 Ω. Since the zero of S_{11} is calibrated in reference to the 50 Ω termination, the uncertainty of the 50 Ω leads to an offset error in low impedance measurement. Similarly, when S_{11} is measured in shunt connection configuration (figure 11 b), S_{11} becomes zero when the DUT admittance is 0 S. Thus, the uncertainty of the 50 Ω leads to a measurement error for high impedance. As a result, the measurable impedance range is restricted. In S_{21} measurement, the uncertainty of the 50 Ω causes a load-match error and affects measurement of low loss factors.

Note that even small offset error leads to a large impedance measurement error in low measurement sensitivity regions (where the vector voltage ratio is near 0 dB), because a small difference in vector voltage ratio is correlated to a greater difference in impedance. In addition to the offset error, susceptibility to temperature variance also significantly affects measurement accuracy as well. (The measurement stability against temperature variance is discussed in section 6.)

(a) Series-through



(b) Shunt-through

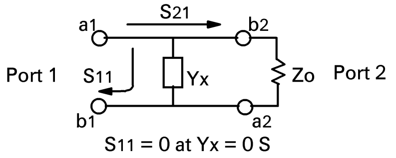
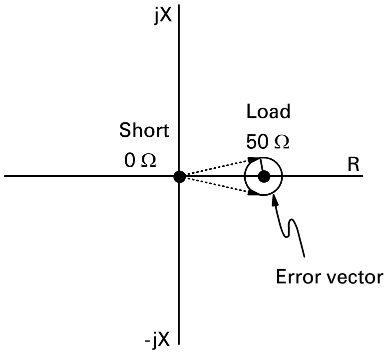


Figure 11. Relationships of S11 to DUT's impedance

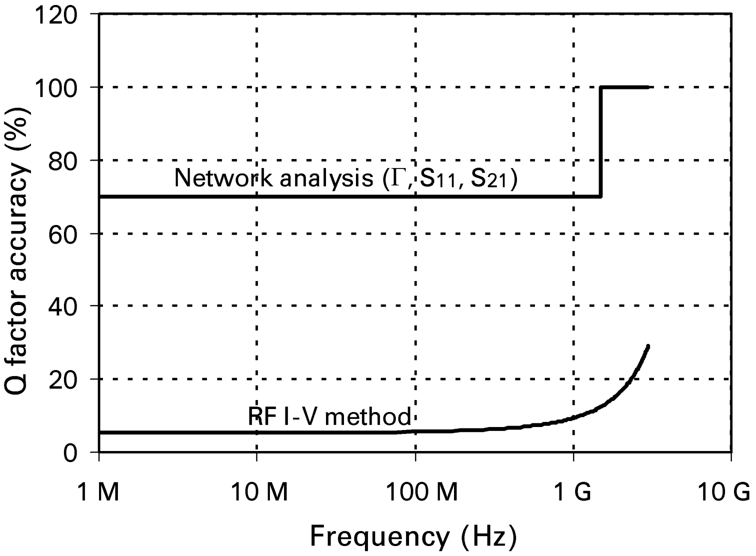


Note: Open impedance is infinit, so it is not shown in the graph.

Figure 12. Phase angle uncertainty of the 50 Ω termination

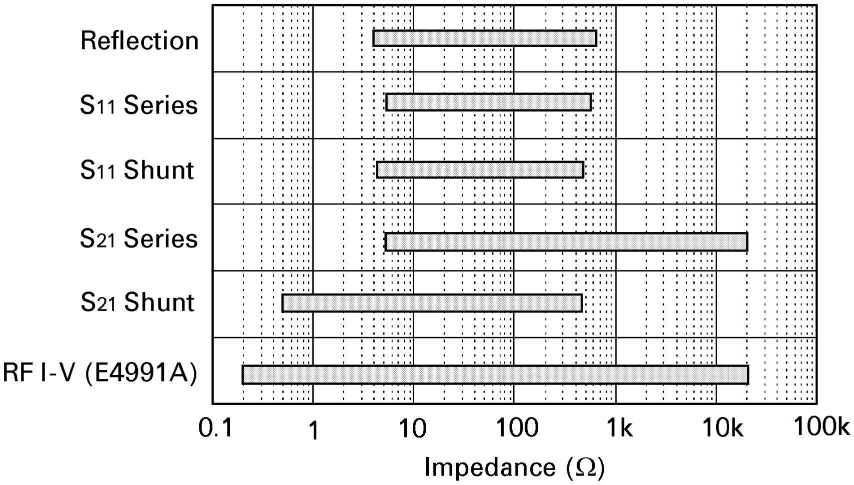
The 0 Ω and 0 S in the RF I-V measurement are calibrated using the short (0 Ω) and open (0 S) terminations, which have much less uncertainty compared to the 50 Ω load termination. Since the calibration ensures less error, the RF I-V method can achieve accurate measurements in low impedance and high impedance regions.

For the evaluation of devices in the RF region, it is often significant to measure the loss factor (D, Q or ESR) rather than the primary parameter (C, L, etc.). To improve the accuracy of loss factor measurements, calibration referenced to a low loss capacitor (LLC) termination can be performed in addition to the open, short and load calibration. The LLC termination provides a reference of impedance with an accurate 90° phase angle in place of the 50 Ω load termination whose phase angle uncertainty increases at higher frequencies (see figure 12). The Q factor accuracy of the RF I-V impedance analyzer compared with the highest performance class network analyzer is shown in figure 13. Improved phase accuracy and stability enable 10 times higher Q accuracy than network analysis. Figure 14 shows the impedance measurement ranges calculated from the accuracy of each measurement method. The reflection coefficient and S-parameter accuracy used in calculation corresponds to the specified accuracy of the best class network analyzer available.



Note : The Q accuracy is compared for a 50 Ω impedance with Q factor of 100. Q error is greater for impedance higher and lower than 50 Ω.

Figure 13. Q measurement accuracy comparison



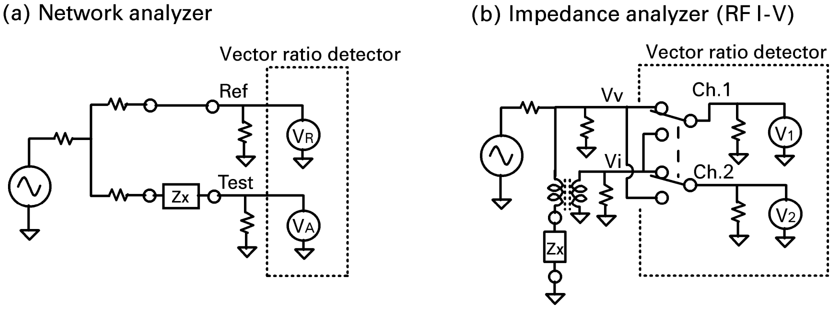
Note: Measurement ranges shown in the graph do not include the limiting factors due to test fixture residuals, variance in test cable parameters and drift of the instrument. The practical impedance measurement ranges for S-parameter methods depend on the test port extension, the test fixture characteristics and the calibration method for eliminating the test-fixture induced errors.

Figure 14. Basic impedance measurement ranges of RF I-V method and network analysis method at 10% accuracy

6. Measurement stability against variance in environmental conditions

Measurement stability after calibration is important for the applications that take a relatively long time, such as when measuring a lot of samples for statistical purposes.Generally, variance in environmental temperature significantly influences the measurement of vector impedance at high frequencies because RF and microwave circuits are susceptible to temperature. In fact, network analyzers require calibration to be performed each time when the instrument is turned on or the frequency setting is changed. RF impedance analyzers also need to be calibrated as well, but provide more stable measurement accuracy after calibration.

Excellent measurement stability is achieved by canceling the tracking error of the vector signal ratio measurement. Figure 15 (a) illustrates the block diagram of the network analyzer. The reference and test channels of the vector voltage ratio detector (VRD) section independently measure the input signals, to take advantage of measurement speed. Tracking error occurs when the relative gain, phase or frequency response of the two channels varies after calibration is performed. Temperature variance is a significant cause of the tracking error, which results in the drift of impedance measurement values. This error differs from unit to unit because the temperature characteristics of the VRD circuits are not identical.


(a) Network analyzer

(b) Impedance analyzer (RF I-V)

Figure 15. Block diagrams of the vector ratio detector section in network analyzer and impedance analyzer.

Figure 15 (b) shows the block diagram of the impedance analyzer using the RF I-V method. The VRD section is configured so that the input signals, Vv and Vi, are multiplexed by the input switch and each signal is alternately measured with two channel VRD circuits in a measurement cycle. In measuring the vector voltage ratio, Vv is firstly measured with channel 1 VRD and, subsequently, channel 2. Vi is measured in the reverse channel order. Since a relative change in the characteristics of the two VRD channels causes opposing error vectors for the channel 1 and channel 2 measurement results, the tracking error is cancelled as a result of the vector voltage ratio calculation. Consequently, the vector ratio measurement results are not affected, thus allowing stable impedance measurement results. However, this method takes a longer measurement time than the conventional VRD method.

Note: The propagation characteristics of test cables also vary with temperature and cause measurement instability. Whereas two-port network measurement requires test cables that are tens of centimeters (or inches) long, one-port RF I-V and reflection coefficient methods allow the DUT to be placed near the instrument's test port by using the test fixture, which is directly attachable to the test port.

7. Difference in defined calibration uncertainty in specified accuracy

Figure 16 shows an example of the 10% accuracy curve specified for the RF I-V impedance analyzer. The impedance range between the upper and lower boundaries of 10% accuracy curve becomes narrower at higher frequencies, while the specified measurement range of the network analyzers is almost flat over the entire frequency range. This is because the RF I-V impedance analyzer incorporates particular calibration uncertainties in the definition of accuracy specification. The accuracy is specified when short, open and load (SOL) calibration is performed at the test port. The short calibration presupposes an uncertainty of ± 0.08 nH resulting from short termination connection repeatability. The open calibration presupposes an uncertainty of ± 24 fF due to open termination connection repeatability.

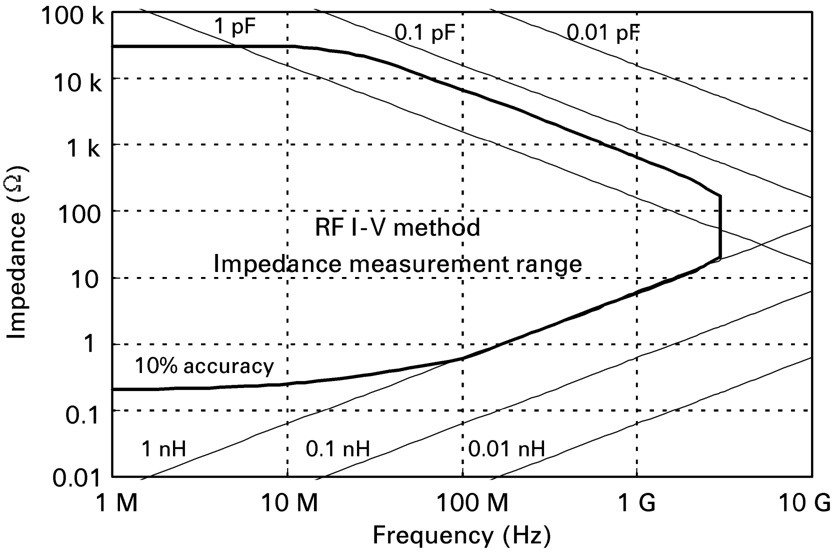


Figure 16. Impedance range of RF I-V impedance analyzer at 10% accuracy

Consequently, the 10% accuracy curves at high frequencies approximate to the reactance lines of 0.8 nH and 0.24 pF, respectively. The accuracy of RF impedance analyzers involves these calibration uncertainties, because the analyzers address to precise characterization of devices, including very low inductance and very low capacitance. Such calibration uncertainty factors are not taken into account for the accuracy of network analyzers. The repeatability of connectors is only included in the specified accuracy as a reflection loss uncertainty because the specifications of network measurement basically assume the measurement configuration being matched to the characteristic impedance, Zo.

8. Correction method to remove test fixture induced errors

To achieve accurate measurements in practice, measurement errors due to the phase shift and residual impedance in the test fixture must be thoroughly removed. In network analysis, performing the full two-port calibration (short, open, load and through calibration) at the tips of the test fixture can maximize the measurement accuracy. Generally, the co-planer waveguide fixture or the micro strip-line fixture is used to optimize impedance matching and frequency characteristics. Calibration for series-through connection type of measurement is performed on the fixture as illustrated in figure 17. This calibration is not easy to accurately perform with actual test fixtures. This is because the required termination devices must be accurate over a broad frequency range and must be precisely positioned at the same place as where the device is inserted. Additionally, these termination devices need to be attached to and removed from the test fixture each time the calibration is performed. Calibration for shunt-through connection type is difficult to appropriately build the open and load termination conditions. Removing the errors by simulating the equivalent circuit of the test fixture obviates the need of the termination devices, but it is subject to analysis and evaluation to establish the equivalent circuit model that agrees with actual characteristics.

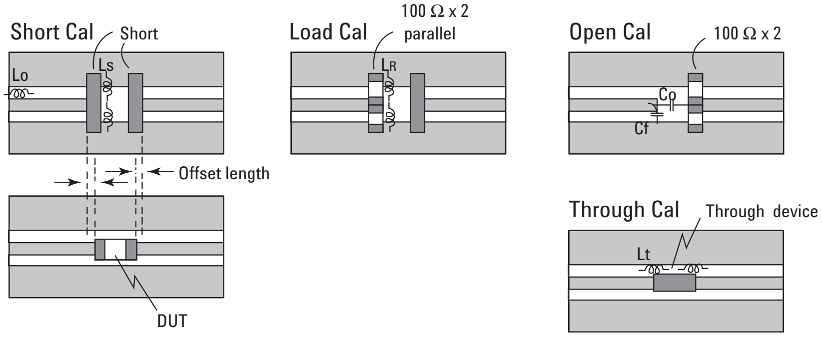
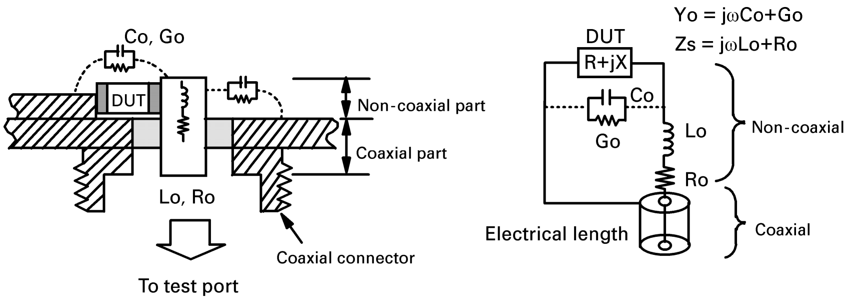


Figure 17. Example of S-parameter measurement calibration on the test fixture

Note: Residual parameters inside and around the termination devices and offset position of the DUT from the calibration plane cause measurement errors.



(a) Typical test fixture configuration

(b) Simplified equivalent circuit model

Figure 18. Example of one-port test fixture and its equivalent circuit model

The RF impedance analyzers offer a wide selection of the test fixtures, which are inexpensive and meet the demanding measurement applications. These test fixtures are designed to allow the DUTs to be accurately positioned at the same state and measured at the shortest possible port-extension length. Since the characteristics of the one-port test fixtures can be represented using a simple equivalent circuit model as shown in figure 18, measurement results can be easily compensated for the error sources by performing the built-in compensation functions of the RF impedance analyzers. For the concepts of calibration and compensation incorporated in the RF impedance analyzer, refer to Appendix B.

9. Conclusion

The RF impedance analyzers employ the RF I-V measurement method, which can measure the DUTs away from 50 Ω with a higher measurement stability than conventional reflection coefficient and S-parameter methods employed by network analyzers. In addition, the RF impedance analyzers have advantages over network analyzers in accurate measurements of a device's parasitics and low loss factors (low D, low ESR or high Q). These advanced impedance measurement capabilities in the RF region provide vital solutions to evaluation needs of passive components (such as chip inductors, capacitors and varactor diodes), which are used in RF telecommunication equipment.

In the characterization of these devices, the RF I-V method has nearly a constant measurement sensitivity from low impedance to high impedance values. To enhance the ability to measure small parasitics and low loss factors, the RF impedance analyzers achieve stable measurements over a wide impedance range by the RF I-V method, as well as low temperature dependence by the vector ratio detector configuration which is free from tracking errors.

The accuracy of RF impedance measurement significantly depends on the calibration method and test-fixture-induced-errors in addition to the operating performance of the instrument. The RF impedance analyzers can be calibrated using a low loss capacitor termination as phase reference to improve measurement accuracy for low loss (high Q) factors. Direct attachment type test fixtures designed for the RF impedance analyzers allow DUTs to be connected with a minimum test-port extension. Since the characteristics of these test-fixtures are known and can be represented by a simple residual impedance and stray admittance model, the built-in compensation functions of the RF impedance analyzers can easily eliminate the measurement errors due to test fixture residuals. With its wide impedance range, stable measurement and ease of error compensation, the RF impedance analyzers provide the best solutions to accurate impedance measurement needs for two terminal devices.

10. Advanced solutions of the E4991A RF impedance/material analyzer

The Agilent E4991A RF Impedance/Material Analyzer extends the impedance measurement solutions by the RF I-V method to 3 GHz, satisfying the evolving needs of cellular telecommunications. By integrating the RF I-V method and other unique measurement techniques, the E4991A allows accurate characterization of the devices even in the impedance regions away from 50 Ω and, resolves the difficulties pertaining to conventional network analysis methods. The advantages of the RF I-V measurement technique provide high-resolution and stable measurement results, thus allowing analysis of the frequency characteristics and equivalent circuit parameters to be accomplished much easier than ever. In the RF circuit design environment, accurate measurement results at the actual operating frequencies offer reliable device characteristic data required for electronic design automation (EDA) tools. The E4991A delivers the benefits of high accuracy, stability and user friendly operating environment for a wide variety of impedance measurement applications.

Appendix A

Consideration for the influences of measurement discrepancies on stability test

Figure A-1 shows the mean values of the measured inductance, capacitance and ESR, which are obtained in the measurement stability test. Despite the same DUTs being measured, the results are different for each measurement method because the calibration inaccuracy, test-fixture residuals (which slightly remain after being compensated), electrical length inaccuracy, and other sources of error influence the measurement. Particularly, the measured ESR values, which are small vector components of measured impedance, are apt to exhibit large discrepancies. Such measurement discrepancies raise an issue on consistency of the measurement stability test conditions. This issue can be clarified by theoretically simulating the variances at virtually the same L, C and ESR measurement values and comparing the results, as described below:

When assuming the same measurement values for all the measurement methods, they can be designated as being the same as the mean values of the RF I-V method (E4991A). Although the discrepancies of the measured ESR values are large as seen in the graphs in figure A-1, the magnitudes of measured impedance are much the same. (The ESR is a small vector component and is insignificant compared to the magnitude of vector impedance.) Also, the detected vector voltages approximate to those for the assumed measurement values. Since the differences in the detected voltages due to the measurement discrepancies are less than approximately 4 dB, they do not significantly influence the variances in the detected voltages as well. (Practically, the variance corresponds to the trace noise of the network analyzer and is not sensitive to the measured levels when the measured signals are sufficiently large).

Therefore, the variances in L, C and ESR measurement values compensated for the measurement discrepancies can be calculated as follows:

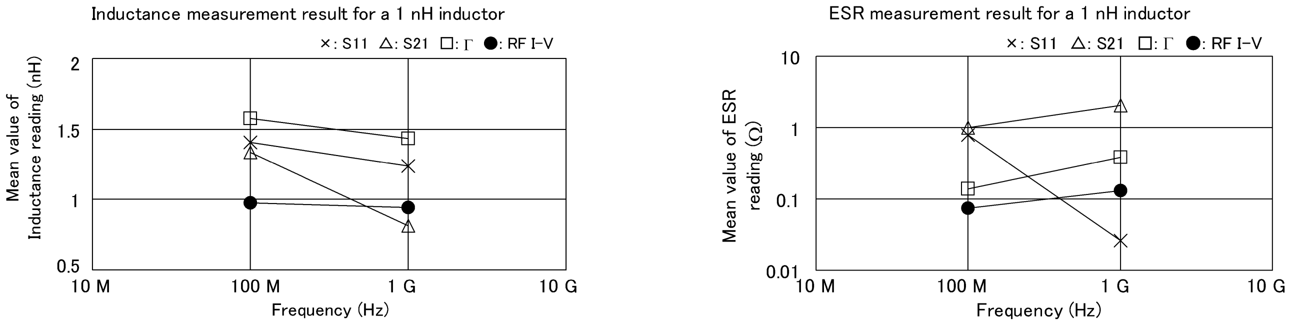
$$\text{Variance} = \psi(\alpha+ß) - \psi(\alpha)$$

Where, $\psi(x)$: Equation to calculate L, C or ESR values from the voltage ratios

α: The theoretically derived vector voltage ratios for the assumed measurement values

ß: Actual variance data for the detected vector voltage ratios (Γ, S_{11} and S_{21} values)

The calculation results are plotted on the graphs shown in figure A-2. These variance data are very similar to the measurement repeatability test results shown in figure 5. Accordingly, the discrepancies of the measured values between the measurement methods are insignificant when examining measurement stability.



Note: Γ, S11 and S21 data in the above graphs represent the inductance and ESR values translated from one-port reflection coefficient (Γ) and two-port S11 and S21 measurement values, respectively. Measured inductance in Γ method involves residual inductance of 0.4 nH (typical), which is defined for the short compensation device of the 16196A test fixture and for which the network analyzer cannot compensate. Subtract 0.4 nH from the measured values to correct for the residual inductance. S11 and S21 measurements are made using the series-through type of DUT connection configuration.

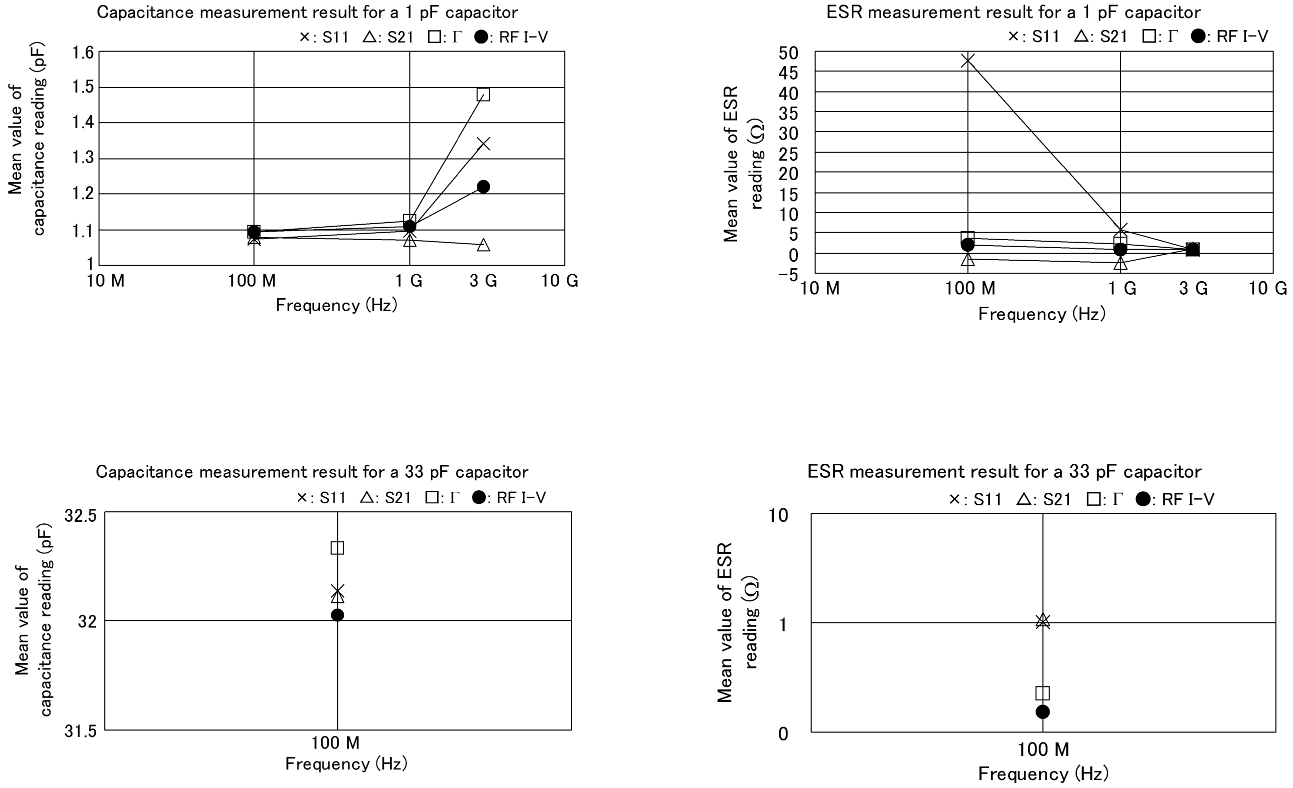
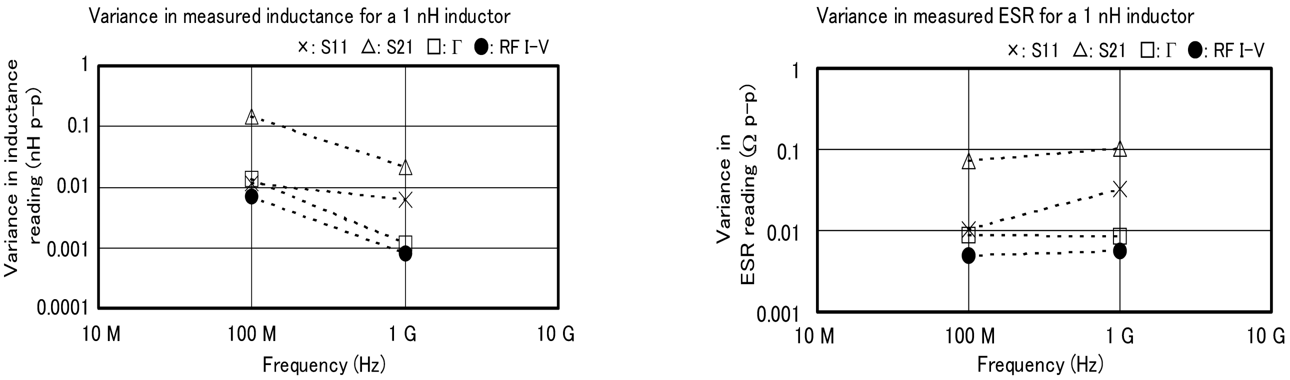


Figure A-1. The mean values of the measured capacitance, inductance and ESR for the measurement stability test results



Note: Γ, S11 and S21 data in the above graphs represent the variance in inductance and ESR values translated from one-port reflection coefficient (Γ) and two-port S11 and S21 measurement values, respectively. S11 and S21 measurements are made using the series-through type of DUT connection configuration.

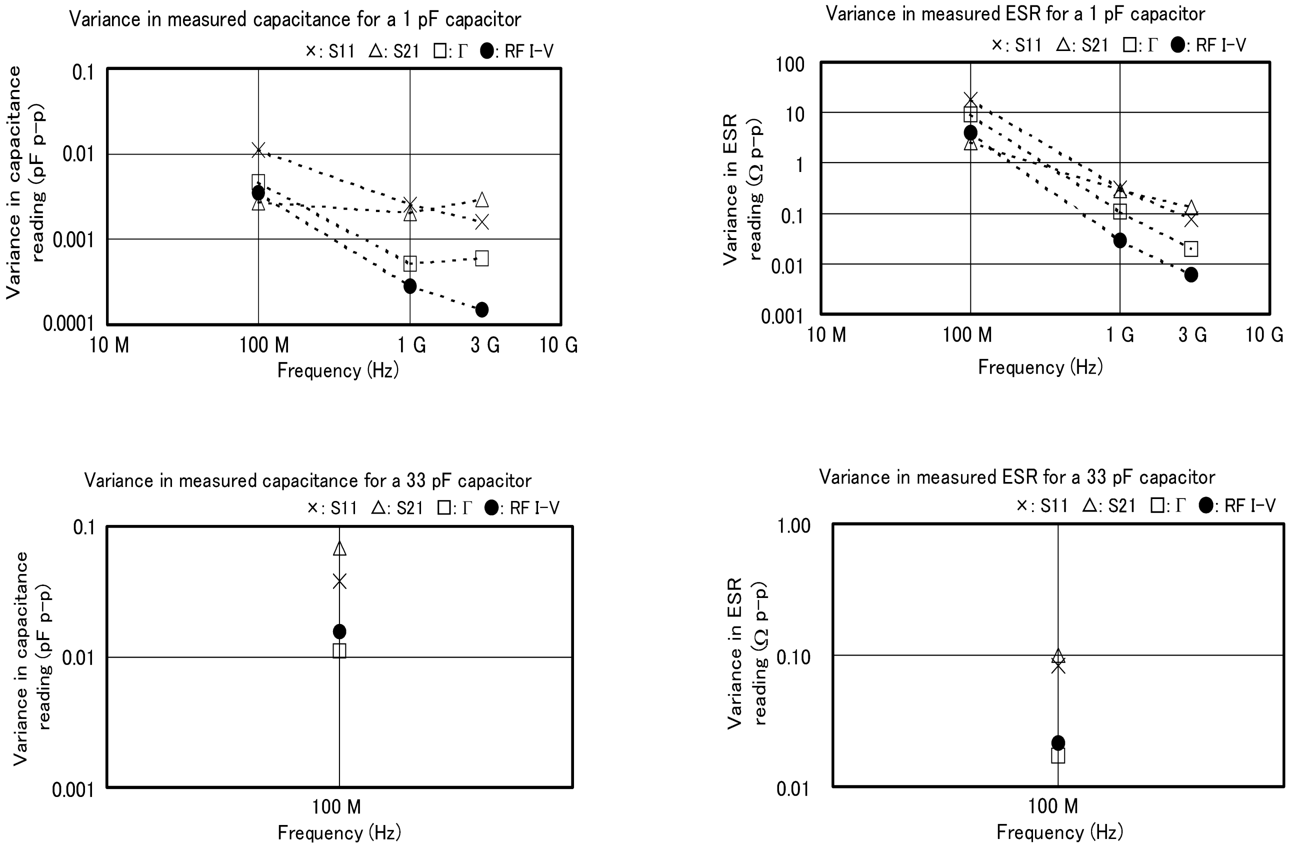


Figure A-2. Simulation results for variance in inductance, capacitance and ESR values compensated for the measurement discrepancies

Appendix B

Concepts of calibration and compensation in impedance analyzers

The RF impedance analyzers are calibrated at the test port of the instrument. The calibration defines the “calibration plane” where the measurement accuracy is specified. When the test port is extended, calibration should be performed at the end of extension, but the measurement accuracy is degraded compared to the measurements without port extension. To measure DUTs, a test fixture needs to be used because devices do not geometrically fit to the test port connector (coaxial connector). In normal measurement setups, the residual impedance of the test fixture is added between the calibration plane (test port) and the DUT, which is connected to the measurement terminals of the test fixture, as shown in figure B-1. Test fixture compensation for impedance analyzers corresponds to fixture de-embedding with network analyzers. The compensation functions of the impedance analyzers can eliminate the measurement errors due to the residuals between the test port and the DUT. The compensation minimizes the additional measurement errors and does not improve accuracy of the calibrated instrument. Compensation requires calibration to be performed initially and cannot replace calibration. The test fixtures for RF impedance analyzers consist of two electrically different sections: coaxial connector section and non-coaxial measurement terminal section (as shown in figures 18 and B-1.) The RF impedance analyzers have two compensation functions to correct measured values for the error sources in these different fixture portions as follows:

Open and short compensations

The characteristics of non-coaxial measurement terminals are represented by a residual impedance and stray admittance model, as shown in figures 18 and B-1. The residual impedance and stray admittance values can be obtained by measuring impedance/admittance with measurement terminals shorted and opened, respectively. The measured open and short values are memorized in the instrument and used for correcting the measured values of the DUTs.

Electrical length compensation

The electrical length compensation corrects measured values for the errors due to the phase shift of the test signal in the coaxial part of the test fixture. Entering the specified electrical length value or designating the model number of the test fixture is required to perform the compensation. Compensation is not performed for magnitude error because the coaxial part of the test fixture is short enough to neglect the propagation loss (attenuation) of the test signal.

For the details of the calibration and compensation theory, refer to the Impedance Measurement Handbook (P/N 5950-3000).

Note: For S-parameter measurements, the Application Note 1364-1 “Agilent De-embedding and Embedding S-Parameter Networks Using a Vector Network Analyzer” (P/N 5980-2784EN) will help you understand the fixture effects and calibration technique concepts.

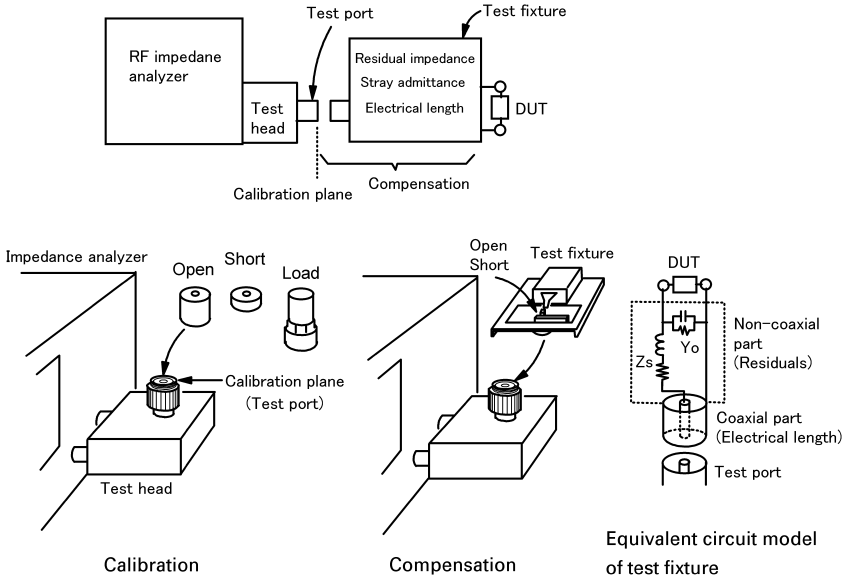


Figure B-1. Calibration and compensation concepts of impedance analyzer

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