# 利用網路分析儀建構新阻抗量測解決方案與應用
# Impedance Measurements using Vector Network Analyzers

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## Keysight authorized distributor

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- 專業AE 團隊 / 設有開放實驗室
- 提供到府教育訓練

## Agenda

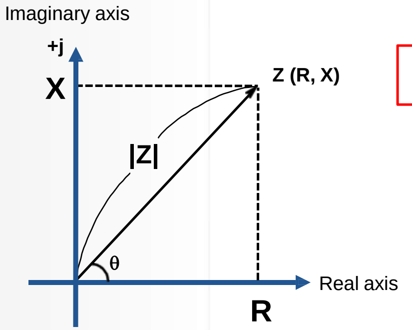
- Impedance analysis basics
- Performing impedance analysis with a Vector Network Analyzer (VNA)
- Impedance measurement methods
- Calibration techniques for ensuring accurate results
- Measurement examples
- Summary


•延伸閱讀： RLC meter(電容電阻電感錶)
•延伸閱讀：查看如何使用網路分析儀量測阻抗
•延伸閱讀：LCR meter自動記錄軟體編程教學

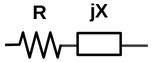


## Definition of Impedance

Impedance (Z): Total opposition a device or circuit offers to the flow of AC




$$Z = R + jX$$




$$R = |Z| \cos\theta$$
$$X = |Z| \sin\theta$$
$$|Z| = \sqrt{R^2 + X^2}$$
$$\theta = \tan^{-1}(X/R)$$

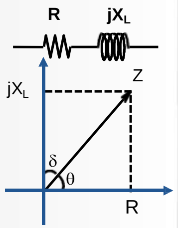
Unit of impedance: ohm (Ω)

## Impedance parameter examples

**L** (Inductance)

$X_L = 2\pi f L = \omega L$

$\omega$: Angular frequency ($= 2\pi f$)

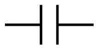



Inductive vector on impedance plane

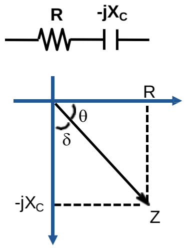
**Q** = quality factor = $\frac{X_L}{R} = \frac{-X_C}{R}$

= tan θ

**C** (Capacitance)



$X_C = \frac{1}{2\pi f C} = \frac{1}{\omega C}$




Capacitive vector on impedance plane

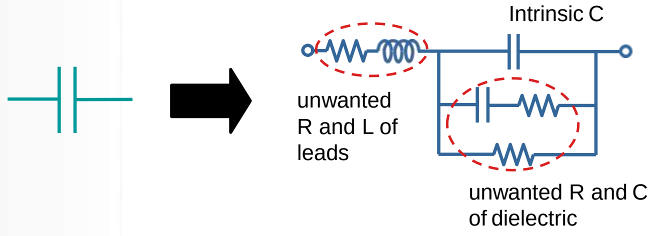
**D** = dissipation factor = $\frac{1}{Q}$

= tan δ



## Parasitic

- **No real components are purely resistive or reactive**
  - Every component is a combination of R, C and L elements
  - The unwanted elements are called **parasitics**




**Capacitor equivalent circuit**

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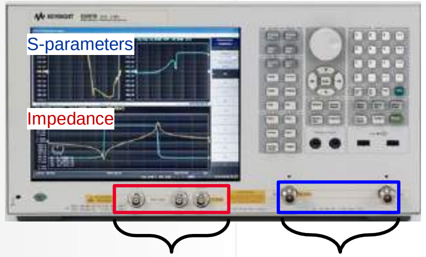
## Impedance measurements with a network analyzer

Ex. Keysight E5061B ENA (Option 3L3/3L4/3L5)

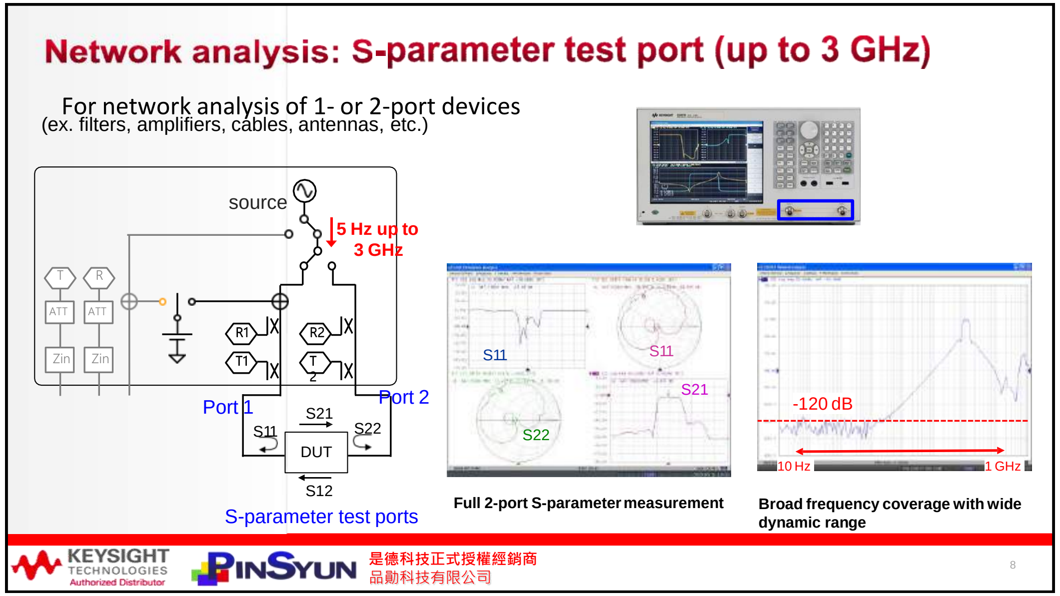



Gain-phase test ports
(5 Hz to 30 MHz)

S-parameter test ports
(5 Hz up to 3 GHz)

**Features**

- S-parameter test ports (5 Hz to 0.5 / 1.5 / 3 GHz)
- Gain-phase test ports (5 Hz to 30 MHz)
- Impedance analysis capabilities (Option 005)
- Built-in DC bias source (up to +-40 Vdc)
- Supports connection with various test fixtures


Network analysis: S-parameter test port (up to 3 GHz)
For network analysis of 1- or 2-port devices
(ex. filters, amplifiers, cables, antennas, etc.)
source
5 Hz up to 3 GHz
T
R
ATT
ATT
Zin
Zin
R1
T1
R2
T2
Port 1
Port 2
S21
S11
S22
DUT
S12
S-parameter test ports
S11
S11
S21
S22
Full 2-port S-parameter measurement
-120 dB
10 Hz
1 GHz
Broad frequency coverage with wide dynamic range
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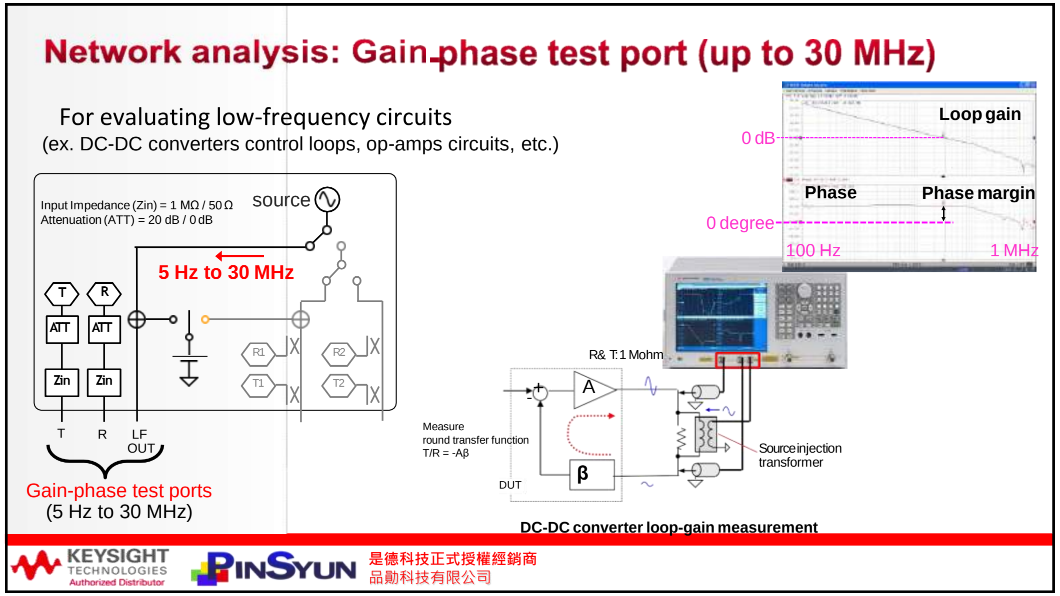
8


Network analysis: Gain-phase test port (up to 30 MHz)
For evaluating low-frequency circuits
(ex. DC-DC converters control loops, op-amps circuits, etc.)
Input Impedance (Zin) = 1 MΩ / 50 Ω
Attenuation (ATT) = 20 dB / 0 dB
source
5 Hz to 30 MHz
T
R
ATT
ATT
Zin
Zin
R1
T1
R2
T2
T
R
LF OUT
Gain-phase test ports
(5 Hz to 30 MHz)
0 dB
Loop gain
Phase
Phase margin
0 degree
100 Hz
1 MHz
R& T:1 Mohm
A
β
Measure
round transfer function
T/R = -Aβ
DUT
Source injection transformer
DC-DC converter loop-gain measurement
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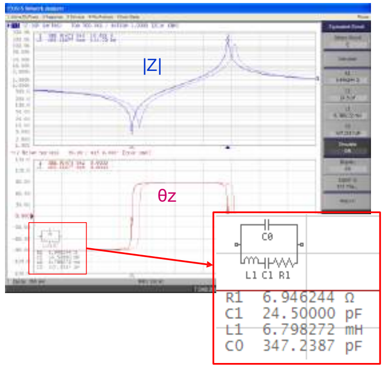
# Impedance measurements with a network analyzer

## IMPEDANCE ANALYSIS SOFTWARE (E5061B OPT.005)

- Fully support basic impedance analysis functions
  - Display impedance parameters
  - Calibration, fixture compensation
  - Equivalent circuit analysis
- Multiple measurement methods
- DC biased impedance measurement
  (0 to ±40 Vdc, max 100 mAdc)

Comparably accurate impedance measurements

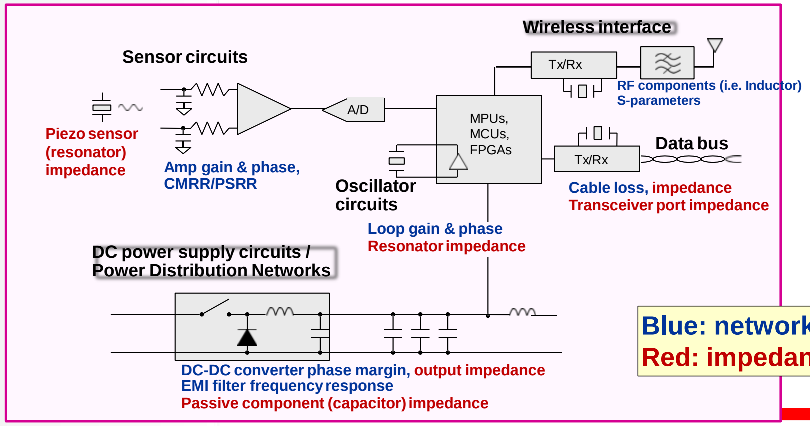



Equivalent circuit analysis with the E5061B option 005



# Benefits of a "combo" solution

## NETWORK ANALYSIS + IMPEDANCE ANALYSIS




Blue: network analysis
Red: impedance analysis

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## Impedance measurement solutions

**Impedance Analyzers & LCR Meters**

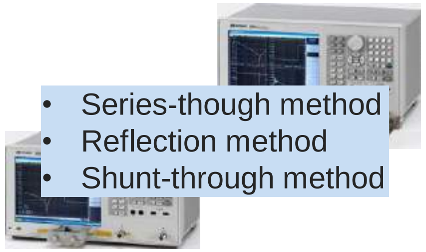
- Auto balancing bridge method
- RF I-V method

✓ Dedicated to impedance measurements

✓ Best impedance accuracy

✓ Covers low to very high impedance range

**Impedance Analysis with Network Analyzers**



- Series-though method
- Reflection method
- Shunt-through method

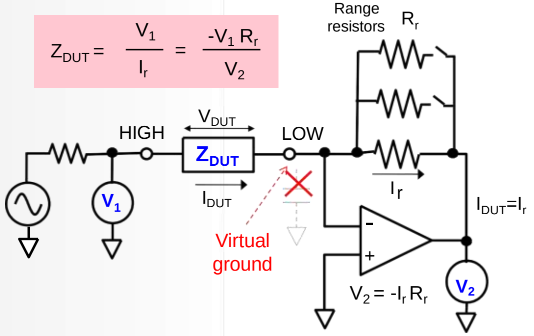
✓Impedance analysis capabilities built into a vector network analyzer (VNA)

✓Solid performance / accuracy

✓ Covers very low to high impedance range

## Auto balancing bridge method

$$Z_{DUT} = \frac{V_1}{I_r} = \frac{-V_1 R_r}{V_2}$$



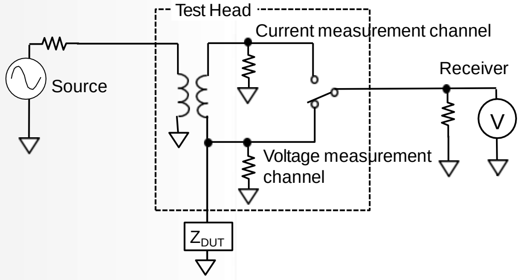

Auto-balancing bridge method

- 20 Hz up to 120 MHz (E4990A)
- Best accuracy (0.045 % typ.)
- Very wide impedance measurement range

Keysight E4990A
Impedance Analyzer



## RF I-V method




RF I-V method

- 1 MHz to 3 GHz (E4991B)
- Less accurate than the auto-balancing bridge; More accurate than the NA-based reflection method
- Excellent stability by measuring voltage & current with a single receiver

Keysight E4991B
Impedance Analyzer

## Impedance measurement range using a network analyzer

Wide impedance measurement range is covered with three methods with a network analyzer.

| Measurement method with NA | Applicable impedance range |
|---|---|
| Series-through | Mid - High |
| Reflection | Mid |
| Shunt-through | Low - Mid |

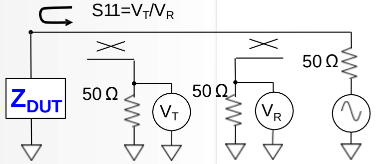
1 m 10 m 100 m 1 10 100 1 k 10 k 100 k

Impedance [ohm]

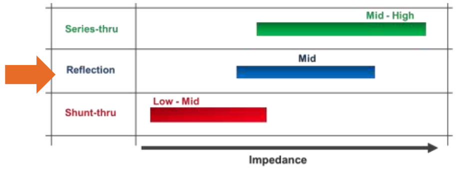


## Reflection method with a vector network analyzer


Keysight E5061B Vector Network Analyzer




$Z_{DUT} = 50 \times (1+S11)/(1-S11)$

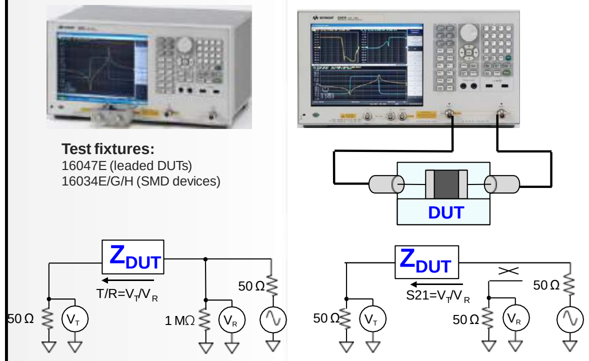


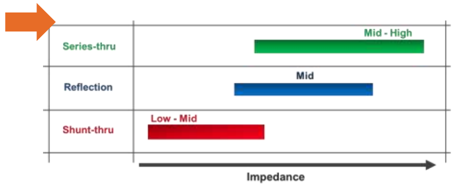

- 5 Hz to 3 GHz (E5061B)
- S11 measurement with built-in directional bridge in the analyzer
- For low to mid- impedance range (ex. **1 Ω to 2 kΩ**)
- Test fixtures with 7 mm connector

## Series-through method with a vector network analyzer

Series-through with gain-phase ports

Series-through with S-parameter ports




$Z_{DUT}$ = (50 x 2) x ((1-S21) / S21)

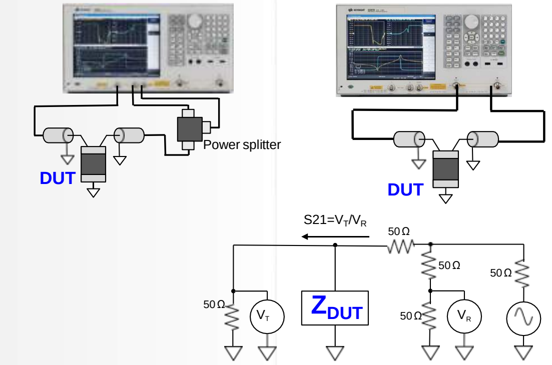
- 5 Hz to 30 MHz (E5061B gain-phase port)
- 5 Hz to several 100 MHz (E5061B S-parameter test port, Port 1 & 2)
- For mid to high impedance range (ex. **5 Ω to 20 kΩ**)
- Test fixtures for gain-phase port

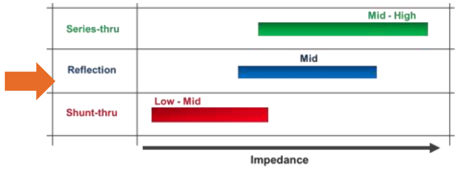


## Shunt-through method with a vector network analyzer

Shunt-through with gain-phase ports

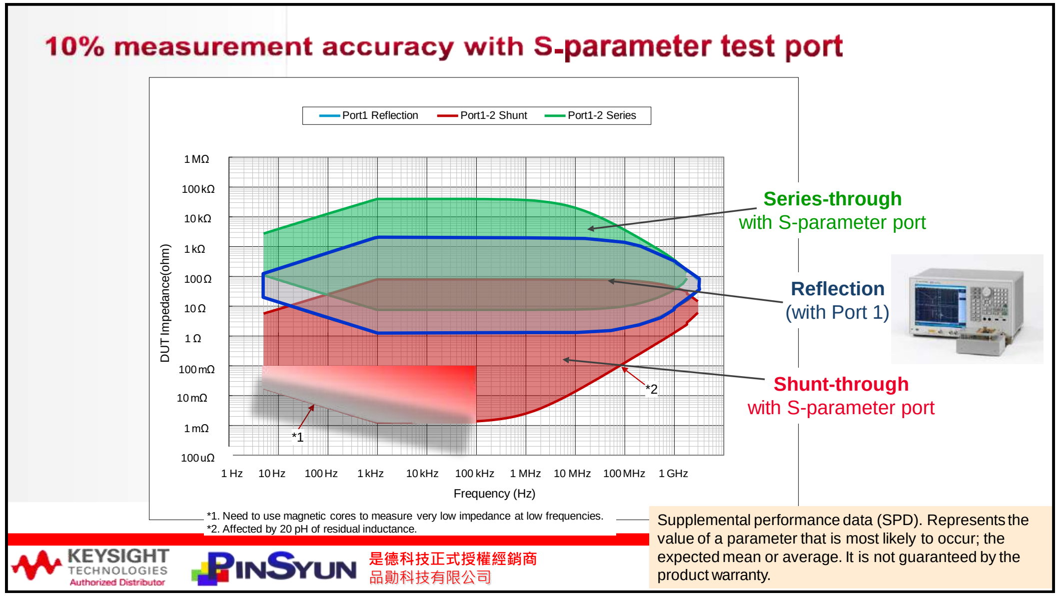
Shunt-through with S-parameter ports




$Z_{DUT}$ = 50 x S21/(2 x (1-S21))

- 5 Hz to 30 MHz (E5061B gain-phase port)
- 5 Hz to 3 GHz (E5061B S-parameter test port, Port 1 & 2)
- For very low impedance range (ex. **1 mΩ to 5 Ω**)
- Home-made fixture or RF probes are required for DUT connection.



10% measurement accuracy with S-parameter test port
Port1 Reflection
Port1-2 Shunt
Port1-2 Series
1 MΩ
100 kΩ
10 kΩ
1 kΩ
100 Ω
10 Ω
1 Ω
100 mΩ
10 mΩ
1 mΩ
100 uΩ
DUT Impedance(ohm)
1 Hz
10 Hz
100 Hz
1 kHz
10 kHz
100 kHz
1 MHz
10 MHz
100 MHz
1 GHz
Frequency (Hz)
*1
*2
Series-through
with S-parameter port
Reflection
(with Port 1)
Shunt-through
with S-parameter port
*1. Need to use magnetic cores to measure very low impedance at low frequencies.
*2. Affected by 20 pH of residual inductance.
Supplemental performance data (SPD). Represents the value of a parameter that is most likely to occur; the expected mean or average. It is not guaranteed by the product warranty.
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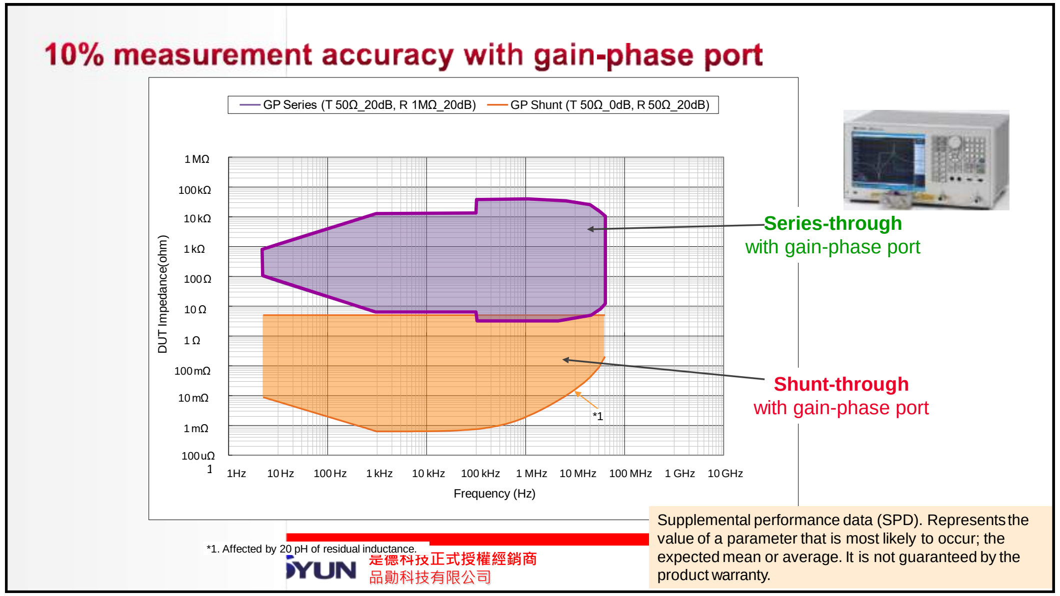

10% measurement accuracy with gain-phase port
GP Series (T 50Ω_20dB, R 1MΩ_20dB)
GP Shunt (T 50Ω_0dB, R 50Ω_20dB)
1 MΩ
100 kΩ
10 kΩ
1 kΩ
100 Ω
10 Ω
1 Ω
100 mΩ
10 mΩ
1 mΩ
100 uΩ
DUT Impedance(ohm)
1 Hz
10 Hz
100 Hz
1 kHz
10 kHz
100 kHz
1 MHz
10 MHz
100 MHz
1 GHz
10 GHz
Frequency (Hz)
*1
Series-through
with gain-phase port
Shunt-through
with gain-phase port
*1. Affected by 20 pH of residual inductance.
Supplemental performance data (SPD). Represents the value of a parameter that is most likely to occur; the expected mean or average. It is not guaranteed by the product warranty.
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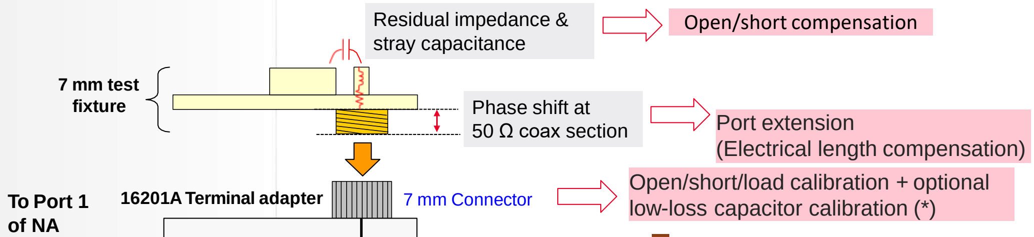
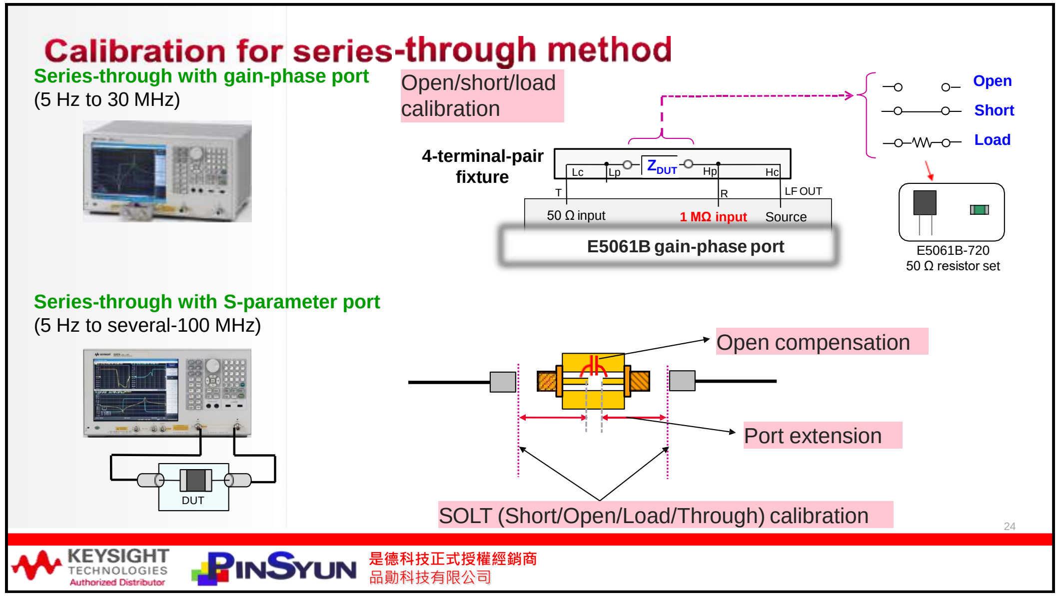
## Calibration for reflection method





* Low-loss capacitor cal improves phase uncertainty of load standard at high frequencies by measuring an air capacitor whose phase angle can be regarded as ideal 90 degree.


Calibration for series-through method
Series-through with gain-phase port
(5 Hz to 30 MHz)
Open/short/load calibration
Open
Short
Load
4-terminal-pair fixture
Lc
Lp
ZDUT
Hp
Hc
T
R
LF OUT
50 Ω input
1 MΩ input
Source
E5061B gain-phase port
E5061B-720
50 Ω resistor set
Series-through with S-parameter port
(5 Hz to several-100 MHz)
DUT
Open compensation
Port extension
SOLT (Short/Open/Load/Through) calibration
24
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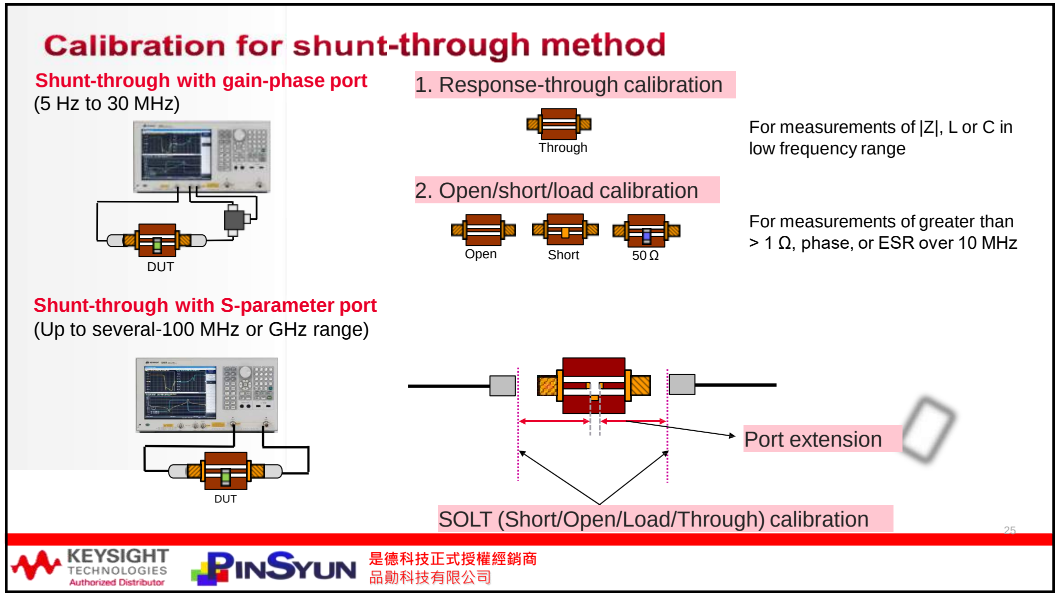
Calibration for shunt-through method
Shunt-through with gain-phase port
(5 Hz to 30 MHz)
DUT
1. Response-through calibration
Through
For measurements of |Z|, L or C in low frequency range
2. Open/short/load calibration
Open
Short
50 Ω
For measurements of greater than > 1 Ω, phase, or ESR over 10 MHz
Shunt-through with S-parameter port
(Up to several-100 MHz or GHz range)
DUT
Port extension
SOLT (Short/Open/Load/Through) calibration
25
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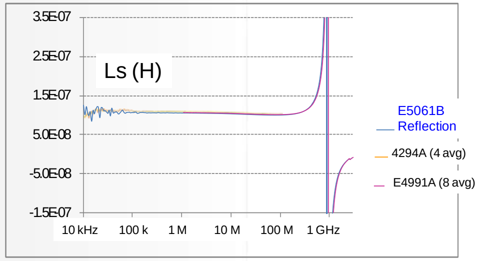
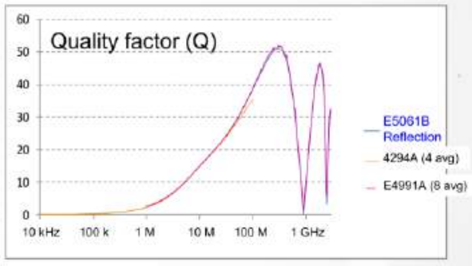
## Example 1) Characterizing 100 nH inductor

**Reflection method** delivers comparable results with dedicated impedance analyzers.




**E5061B ENA setup:**
Setup: 10 kHz to 3 GHz, -10 dBm source power, 30 Hz IF bandwidth. **Reflection method.**
Calibration: Open/short/load calibration & low-loss capacitor calibration, port extension, open/short compensation.

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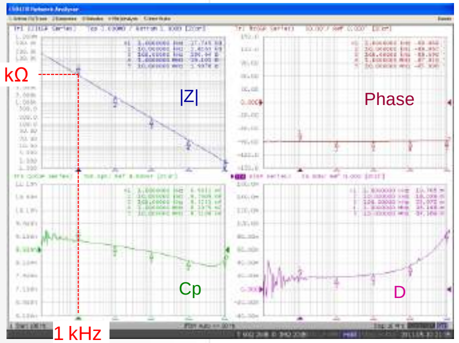
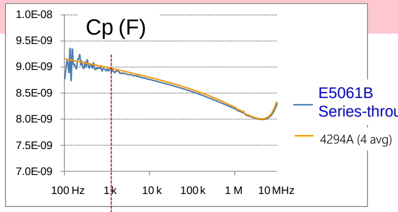
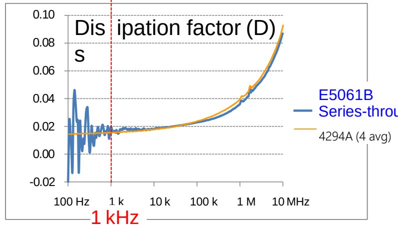
## Example 2) Characterizing 10 nF capacitor

**Series-through method** delivers comparable results with dedicated impedance analyzers for moderate impedance range.



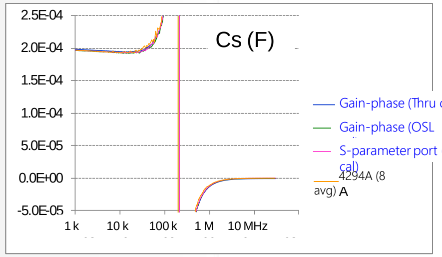



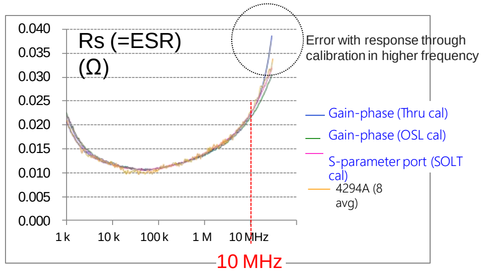

**E5061B ENA setup:**
Setup: 100 Hz to 10 MHz, 0 dBm source power, Auto IF bandwidth (20 Hz limit). **Series-through method** with gain-phase port. Calibration: Open/short/load calibration.



## Example 3) Characterizing 200 uF capacitor

**Shunt-through method** with appropriate calibration technique delivers comparable results with dedicated impedance analyzers.

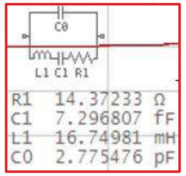


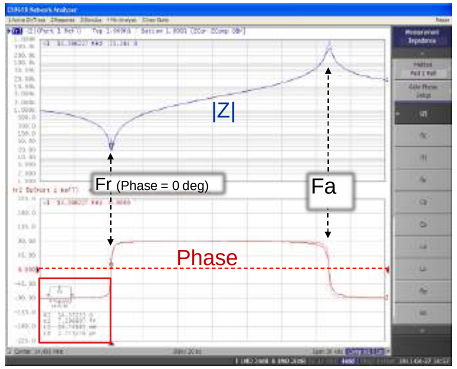




**E5061B ENA setup:**
Setup: 1 kHz to 10 MHz, 0 dBm source power, Auto IF bandwidth (20 Hz limit). **Shunt-through method.**
Calibration:
- gain-phase port: Response through calibration or Open/short/load calibration (T-port ATT = 0 dB)
- S-parameter port: SOLT calibration + port extension. Large magnetic core attached to test cables.

## Example 4) Characterizing crystal resonator

Impedance analysis software computes the equivalent circuit of DUT from measured impedance results.




**E5061B ENA setup:**
Setup: Center frequency 14.4 MHz, -19 dBm source power, 30 Hz IF bandwidth.
Reflection method using 16201A + 16092A 7 mm fixture.

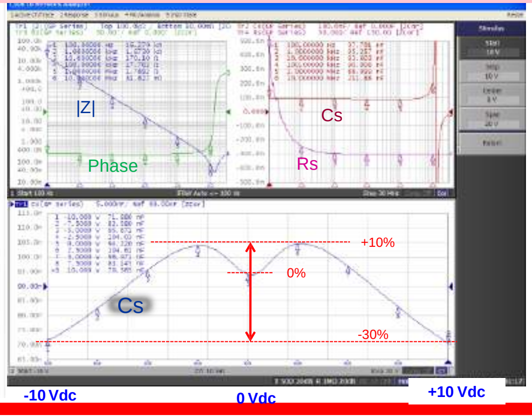


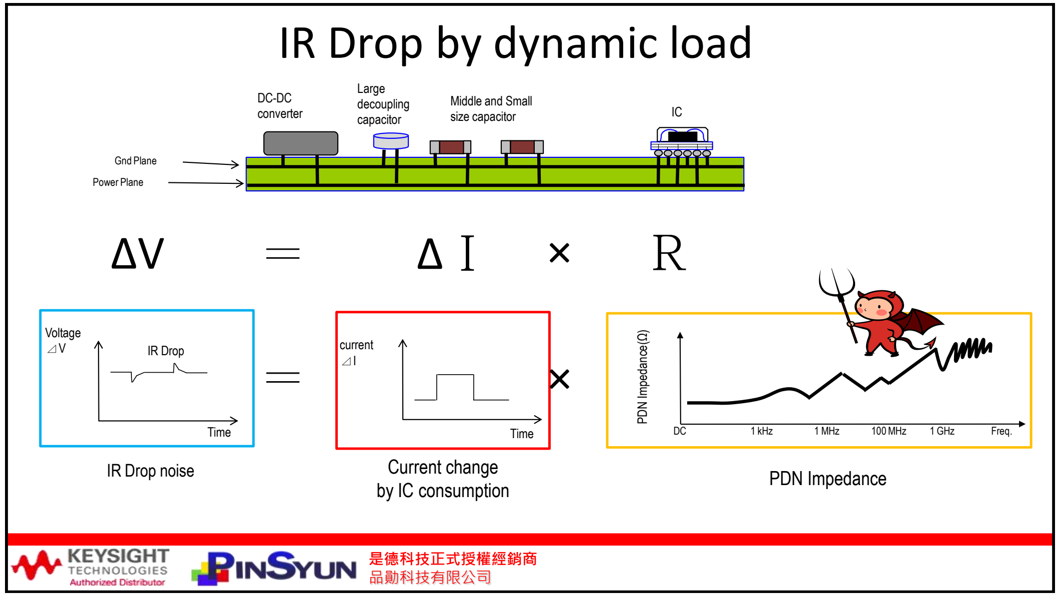
## Example 5) Adding DC bias

The built-in DC bias source is used for characterizing a ceramic capacitor with a strong dependency on the applied DC voltage.

**Frequency sweep**
(100 Hz to 30 MHz)

**DC bias sweep**
(-10 to +10 Vdc,
CW=10 kHz)




IR Drop by dynamic load
DC-DC converter
Large decoupling capacitor
Middle and Small size capacitor
IC
Gnd Plane
Power Plane
ΔV = Δ I × R
Voltage ⊿V
IR Drop
Time
current ⊿I
Time
PDN Impedance(Ω)
DC
1 kHz
1 MHz
100 MHz
1 GHz
Freq.
IR Drop noise
Current change by IC consumption
PDN Impedance
KEYSIGHT TECHNOLOGIES Authorized Distributor
PINSYUN
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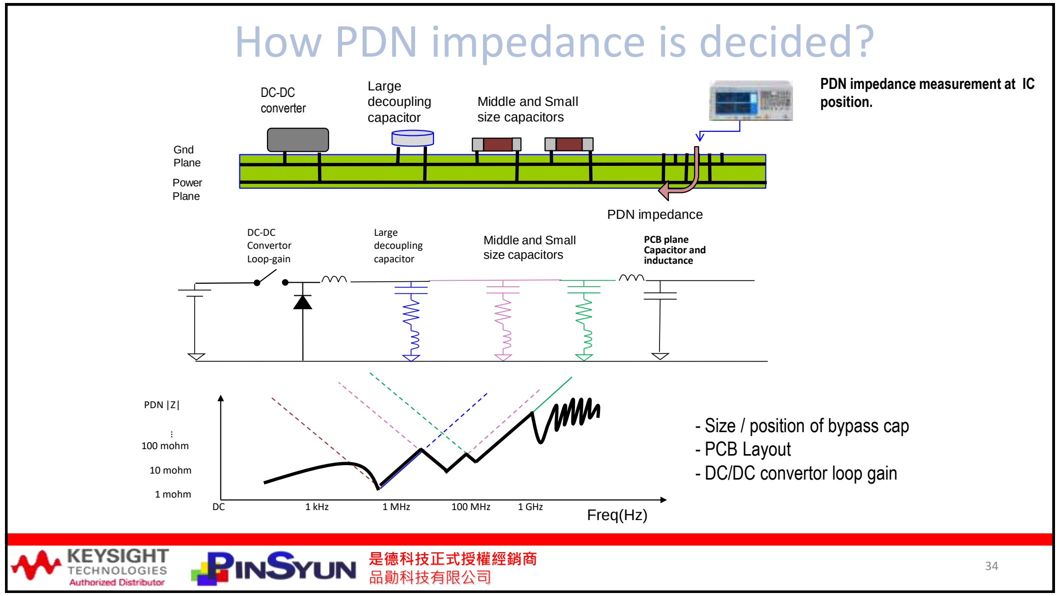
How PDN impedance is decided?
DC-DC converter
Large decoupling capacitor
Middle and Small size capacitors
PDN impedance measurement at IC position.
Gnd Plane
Power Plane
PDN impedance
DC-DC Convertor Loop-gain
Large decoupling capacitor
Middle and Small size capacitors
PCB plane Capacitor and inductance
PDN |Z|
100 mohm
10 mohm
1 mohm
DC
1 kHz
1 MHz
100 MHz
1 GHz
Freq(Hz)
- Size / position of bypass cap
- PCB Layout
- DC/DC convertor loop gain
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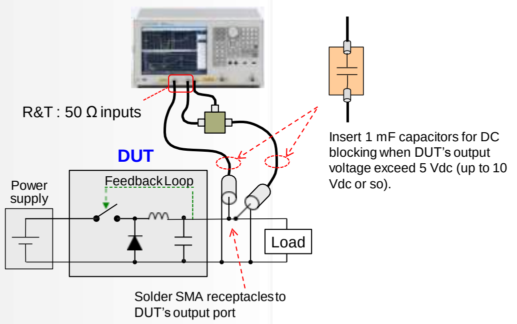
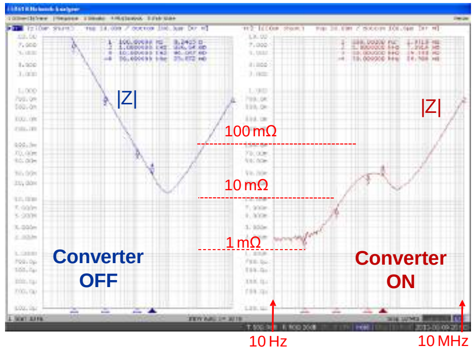
34

## Example 6) Output impedance of DC-DC converter

Extremely low-impedance measurement (in mΩ range) can be achieved with **shunt-through method** using gain-phase port.

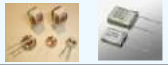
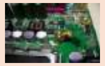



**E5061B ENA setup:**
Setup: 100 Hz to 10 MHz, 10 dBm source power, 10 Hz IF bandwidth). **Shunt-through method** using gain-phase port. T: Zin = 50 ohm, ATT = 0 dB, R: Zin = 50 ohm, ATT = 20dB
Through calibration performed with -10 dBm source power



## Select the best method for your applications

| Frequency range | Impedance range | Recommended method and test port | Example DUTs | |
|---|---|---|---|---|
| Below 100 MHz | <100 mΩ | **Shunt-through method** with gain-phase port (to 30 MHz); S-parameter test port (above 100 kHz) | DC-DC converters, mid or large bypass capacitors, power distribution networks (PDNs) |  |
| | 1 Ω to 10 kΩ | **Reflection method** with S-parameter test port | Inductors, transformers, resonators |  |
| | > 10 kΩ | **Series-through method** with gain-phase port (up to 30 MHz); S-parameter test port (up to 300 MHz) | Small capacitors, resonators, inductors and transformers |  |
| Above 100 MHz | < 100 mΩ | **Shunt-through method** with S-parameter test port | Small bypass capacitors, PDNs |  |
| | 1 Ω to 2 kΩ | **Reflection method** with S-parameter test port | RF Inductors and capacitors, other RF passive components |  |

## Agenda

- Impedance analysis basics
- Performing impedance analysis with a Vector Network Analyzer (VNA)
- Impedance measurement methods
- Calibration techniques for ensuring accurate results
- Measurement examples
- Summary


•延伸閱讀： RLC meter(電容電阻電感錶)
•延伸閱讀：查看如何使用網路分析儀量測阻抗
•延伸閱讀：LCR meter自動記錄軟體編程教學



## Summary

- Impedance analysis capabilities on a network analyzer offer greater versatility on your R&D bench.
- Select the most appropriate impedance measurement method and calibration technique depending on your application.

•延伸閱讀： RLC meter(電容電阻電感錶)
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