KEYSIGHT

元件阻抗特性的測試原理、校準和測試治具選擇

林 文 生 / Vincent Lin, 應用工程部 / 品勛科技
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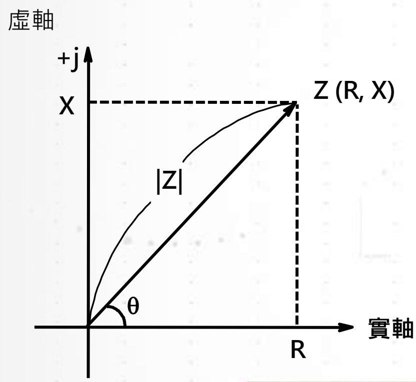
元件的阻抗測試

阻抗Z: 元件或電路對交流電的總的反作用



$$Z = R + jX = |Z|\angle\theta$$

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

阻抗單位: 歐姆ohm (Ω)

|Z|
|Y|
R
X
G
B
Ls
Lp
Cs
Cp
Rs
Rp
Q
D
θz
θy

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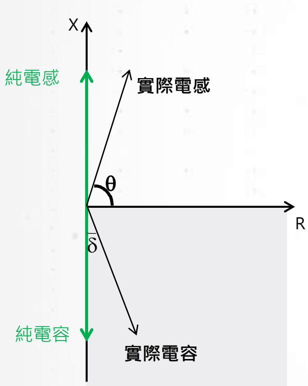
品質因數 Q vs 損耗因數 D

感性元件和容性元件



純電感L　感抗$X_L = 2\pi fL$

實際電感L　R　jX_L　品質因數$Q = \frac{X_L}{R} = \frac{-X_C}{R} = \tan\vartheta$

純電容C

實際電容C　R　$-jX_C$　損耗因數$D = \frac{1}{Q} = \tan\delta$

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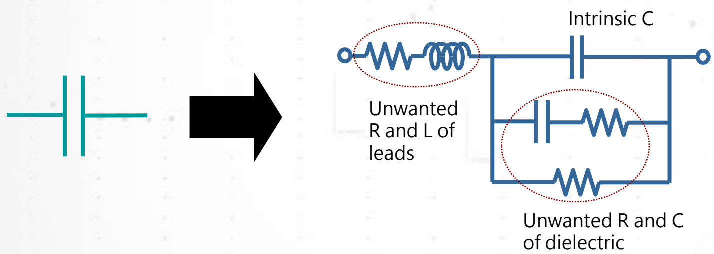
寄生效應

純容性或純感性的元件是不存在的

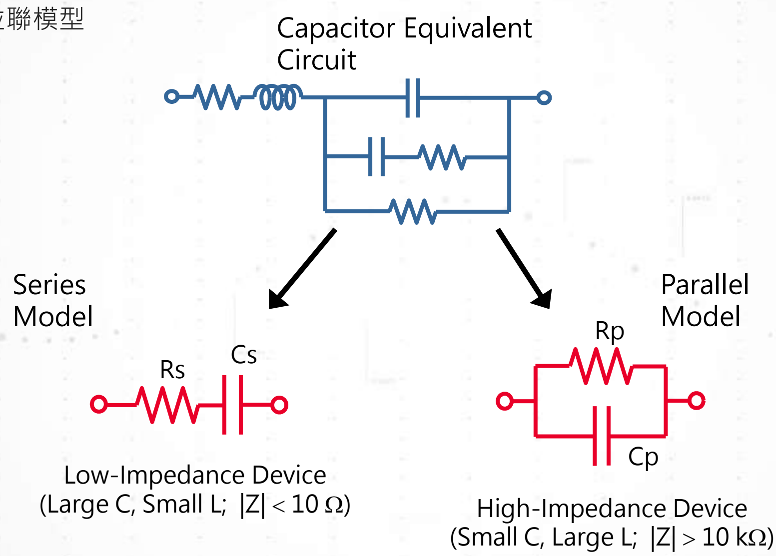
- No real components are purely resistive or reactive
  - Every component is a combination of R, C and L elements
  - The unwanted elements are called **parasitics**



Capacitor Equivalent Circuit

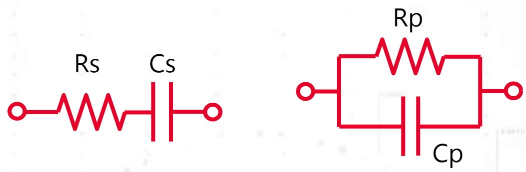
元件阻抗模型

串聯模型和並聯模型



元件阻抗模型

Which Model Is Correct?

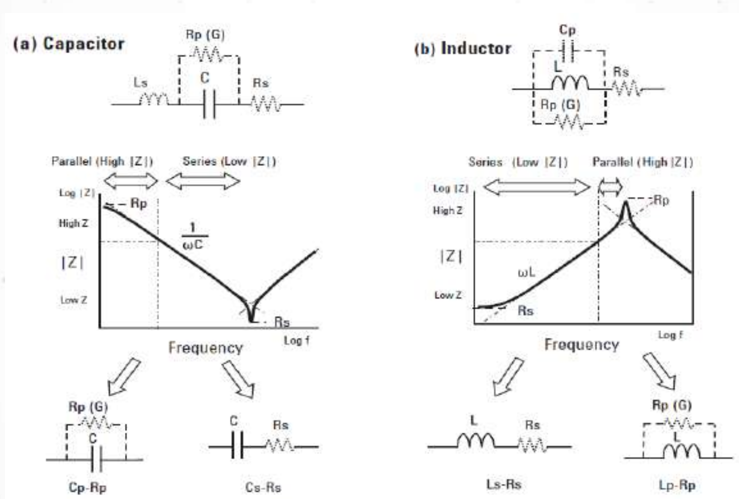


Series model   Parallel model

- Both are correct
  $Cs = Cp (1 + D^2)$
- One is a better approximation
- For high Q or low D components, $C_S \approx C_P$

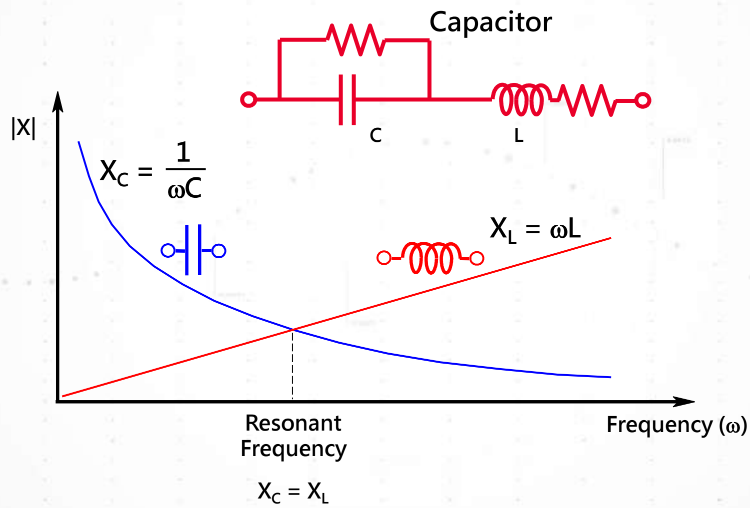
等效電路模型的成分

元件的阻抗會隨信號的頻率變化而變化



隨著頻率變化的電抗

元件的頻響特性



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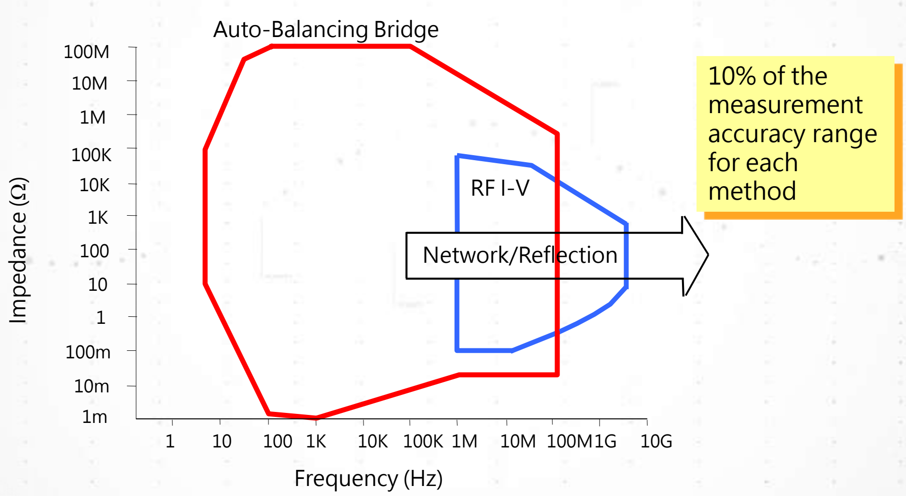
阻抗量測方法

比較自動平衡電橋法/RF I-V法/網路分析儀



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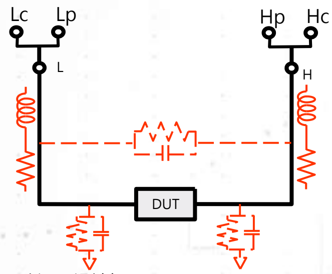
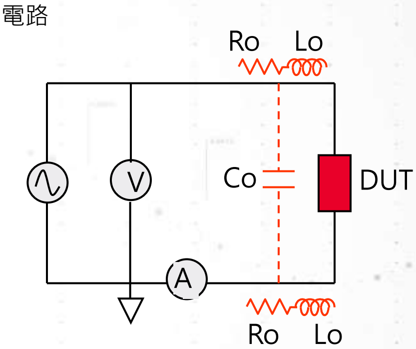
2端(2T)連接

簡單， 但測試範圍有限

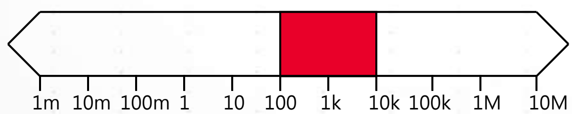
A. 連接方法



B. 電路



C. 阻抗量測範圍 (Ω)



- 最簡單
- 誤差多
- 引線電感/電阻
- 雜散電容

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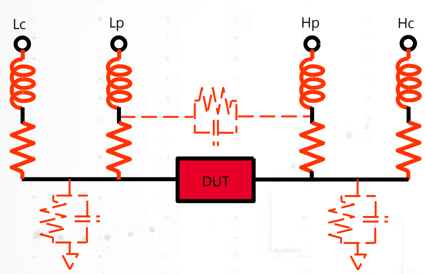
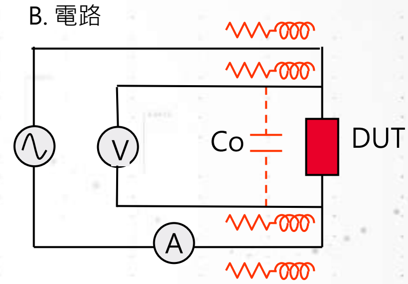
4端(4T)連接

拓展了阻抗的測試量程

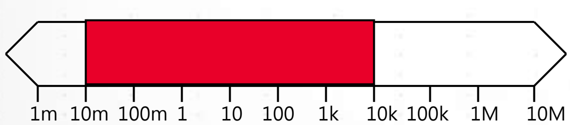
A. 連接



B. 電路



C. 量測阻抗範圍 (Ω)



- 減小引線電感影響
  - ✓ 信號源電流通路和電壓電纜彼此獨立
- 互感問題

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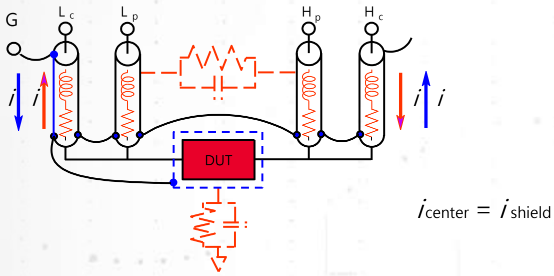
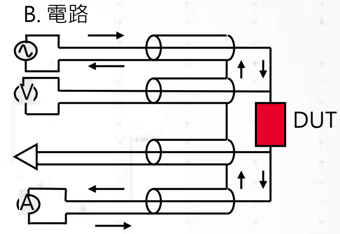
4端對(4TP) 連接

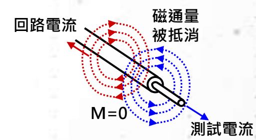
最佳的連接方式

A. 連接

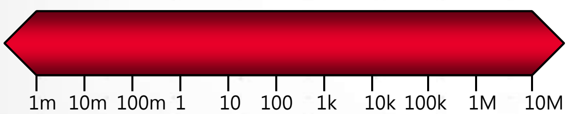


B. 電路





C. 阻抗量測範圍 (Ω)



- 外導體抵消了內導體產生的磁通
- 擴展低阻抗範圍到1毫歐

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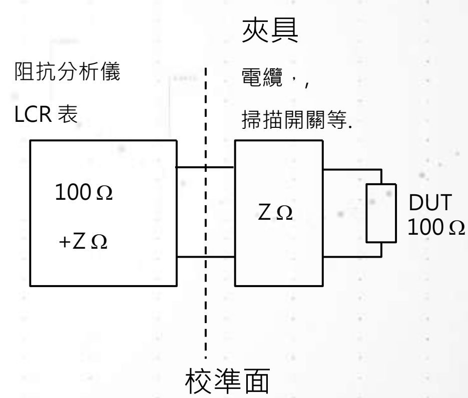
校準與補償

射頻元件測試的必備條件

- 校準：定義一個參考平面，在這個平面上能得到規定的量測精準度，這個平面稱為校準平面。（測試結果可以溯源）
- 補償：抵消掉 DUT 與校準面之間的誤差
  - 兩種補償方法:
    - OPEN/SHORT 補償
    - OPEN/SHORT/LOAD 補償



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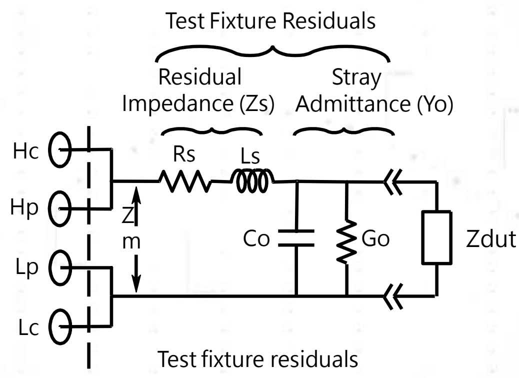
校準與補償

OPEN/SHORT 補償

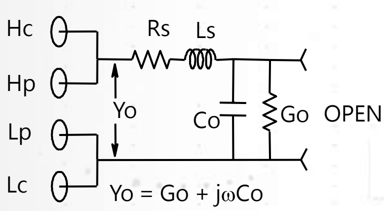


Test fixture residuals

$$Zdut = \frac{Zm - Zs}{1 - (Zm - Zs)Yo}$$

校準與補償

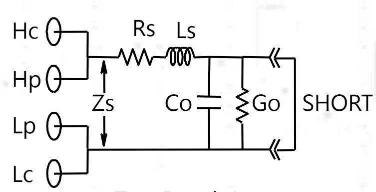
OPEN/SHORT補償原理



Yo = Go + jωCo

$$(Rs + j\omega Ls << \frac{1}{Go + j\omega Co})$$

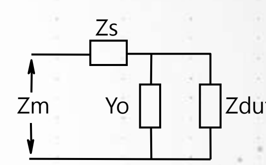
(a) OPEN 量測



Zs = Rs + jωLs

SHORT Impedance << Rs + jωLs

(b) SHORT 量測



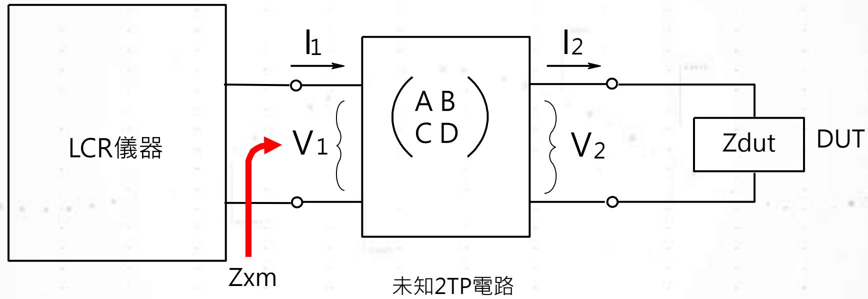
$$Zdut = \frac{Zm - Zs}{1 - (Zm - Zs)Yo}$$

雜散阻抗和 雜散導納

校準與補償

OPEN/SHORT/LOAD 補償

基本理論



Zdut = (A ×V2 + B × I2) / (C × V2 + D × I2) = (A × Zxm + B) / (C × Zxm + D)

where Zdut = V1/I1 and Zxm = V2/I2

校準與補償

OPEN/SHORT/LOAD 補償

基本理論

$$Zdut = \frac{Zstd\,(Zo - Zsm)\,(Zxm - Zs)^*}{(Zxm - Zs)\,(Zo - Zxm)}$$

Zo : OPEN measurement value
Zs : SHORT measurement value
Zsm : Measurement value of the LOAD device
Zstd : True value of the LOAD device
Zxm : DUT Measurement value
Zdut : DUT Corrected value

*上述為複數值，需要轉換為實部和虛部.

測試附件

眾多的測試治具， 滿足眾多不同的測試需求

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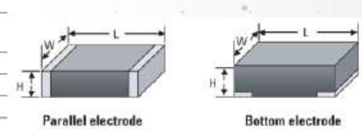
測試治具

Test fixture selection by SMD size

https://www.keysight.com/tw/zh/assets/7018-06727/brochures/5965-4792.pdf

Classi-fication	Test fixture type	Model number	Electrode type	Maximum usable frequency	* Applicable SMD size [code in mm / (EIA code in inch)]*5 0201 / (008005)	0402 / (01005)	0603 / (0201)	1005 / (0402)	1608 / (0603)	2012 / (0805)	3216 / (1206)	3225 / (1210)	4520 / (1808)	4532 / (1812)	5750 / (2220)	Minimum L x W x H (mm)	Maximum L x W x H (mm)
LF, 4TP*1	SMD, General	16034E	Parallel	40 GHz					•	•	•	•	•	•	•	0.1 x 0.5 x 0.5	8 x 10 x 10
	SMD, General	16034G	Parallel	120 MHz			•	•	•	•	•					0.1 x 0.3 x 0.3	5 x 1.6 x 1.6
	SMD, General	16034H	Parallel	120 MHz					•	•	•	•	•	•		0.1 x 0.6 x 0.6	5 x 15 x 3
	SMD, Tweezers*3	16334A	Parallel	15 MHz					•	•	•	•	•	•	•	See Note 7	L < 10
RF, 7 mm*2	SMD/Lead*4	16092A	Parallel	500 MHz					•	•	•	•	•	•	•	See Note 6	L < 18
	SMD, General	16192A	Parallel	2 GHz				•	•	•	•	•	•	•	•	L > 1	L < 20
	SMD/Lead*4	16194A	Bottom	2 GHz						•	•	•	•	•	•	L > 2	L < 15
	SMD, Coaxial	16196A	Parallel	3 GHz					•							1608 size only	
	SMD, Coaxial	16196B	Parallel	3 GHz				•								1005 size only	
	SMD, Coaxial	16196C	Parallel	3 GHz			•									0603 size only	
	SMD, Coaxial	19196D	Parallel	3 GHz		•										0402 size only	
	SMD, General	16197A	Bottom	3 GHz				•	•	•	•	•				1005 to 3225 sizes only	
	SMD, General	16197A-001	Bottom	3 GHz			•	•	•	•	•	•				0603 to 3225 sizes only	
	SMD, General	16198A	Bottom	3 GHz	•	•										0201 to 0402 sizes only	



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Negative D Problem and its Causes

• Negative D Problem

C-D Measurement

- Theoretically, it is not possible to have negative D for passive components.

$$D = \frac{R}{X_C}$$

- Negative D is seen in very low D measurements

DUT: Capacitor C = 100 pF, D = 0.001
@ 1 MHz

R = 1.6

X_C = 1.6 k

$X_C >> R$

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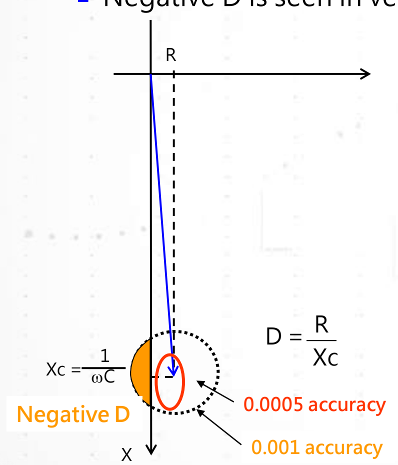
Negative D Problem and its Causes

• Causes of Negative D

1. Inaccurate measurement instruments
   - Negative D is seen in very low D measurements



Example:
C = 100 pF
D = 0.0008 @ 100 kHz, 1 Vrms)

Product	D Accuracy	Possible Readout
4288A	±0.0005	0.0003 to 0.0013
4263B	±0.001	-0.0002 to 0.0018

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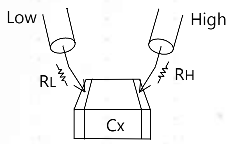
Negative D Problem and its Causes

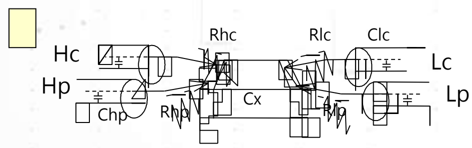
- Causes of Negative D

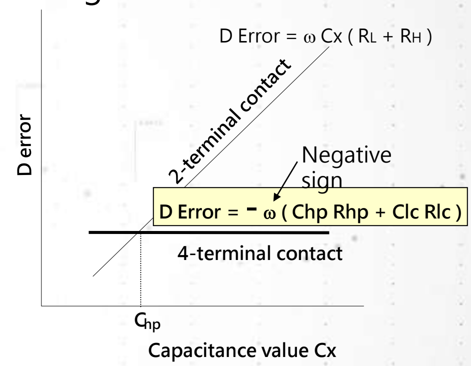
2. Contact resistance in a 4-terminal configuration

- Contact resistance in 2-terminal contact



- Contact resistance in 4-terminal connection





Error caused by Rhp with Chp:

Magnitude error: $\frac{1}{\sqrt{1+\omega^2 Chp^2 Rhp^2}} - 1$ Phase error: ωChp Rhp (rad)

- Contact resistance also degrades SHORT compensation

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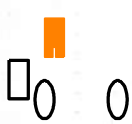
Negative D Problem and its Causes

- Causes of Negative D

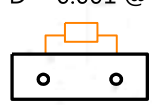
3. Improper SHORT compensation

- Shorting Plate
  (PN: 5000-4226)



- Typical Residuals (@ 1 MHz)
  - Ls = 26 nH
  - Rs = 2 mΩ
  - Rs + jXs = 2 mΩ + j163 mΩ

- Cs = 100 nF
  D = 0.001 @ 1 MHz



Z = R + jX

$= \frac{D}{\omega Cs} + \frac{1}{j\omega Cs}$

= 1.6 m - j1.6

- Measured D

$= \frac{R - Rs}{X - Xs} = \frac{(1.6 - 2) \times 10^{-3}}{1.6 - 0.163}$

= -0.0028

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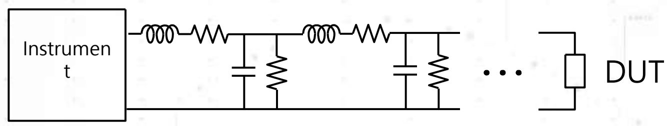
Negative D Problem and its Causes

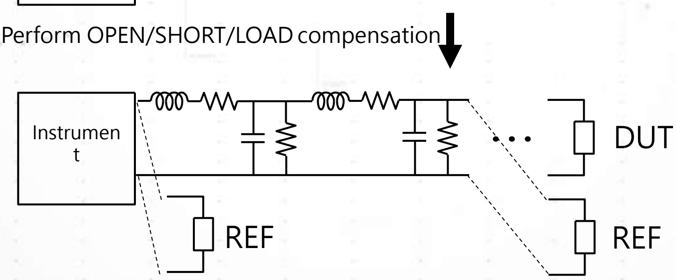
•Causes of Negative D

4. Complicated residuals

- Long Cable, Scanner, Handler
- OPEN/SHORT compensation cannot eliminate the measurement error



- Perform OPEN/SHORT/LOAD compensation



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治具補償

Calibration and Compensation Comparison

	Theory
Calibration	• Eliminates instrument system errors • Defines the "Calibration Plane" using the CAL standard • Low Loss C Calibration improves high Q measurement in RF
Cable correction	• Eliminates the effects of cable error • Extends the "Calibration Plane" to the end of the cable
Compensation	• Eliminates the effects of error sources existing between the "Calibration Plane" and the DUT
OPEN/SHORT Compensation	• Eliminates the effects of simple fixture residuals
OPEN/SHORT/LOAD Compensation	• Eliminates the effects of complicated fixture residuals

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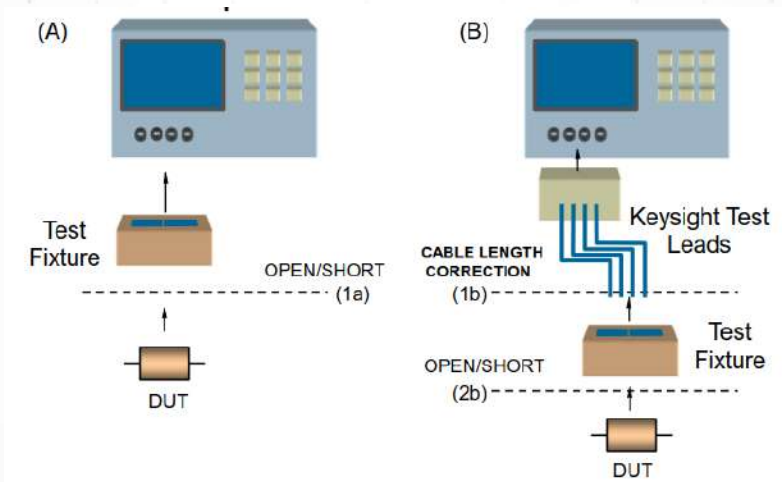
治具補償

Which compensation technique should you use?
- Selection Guideline -



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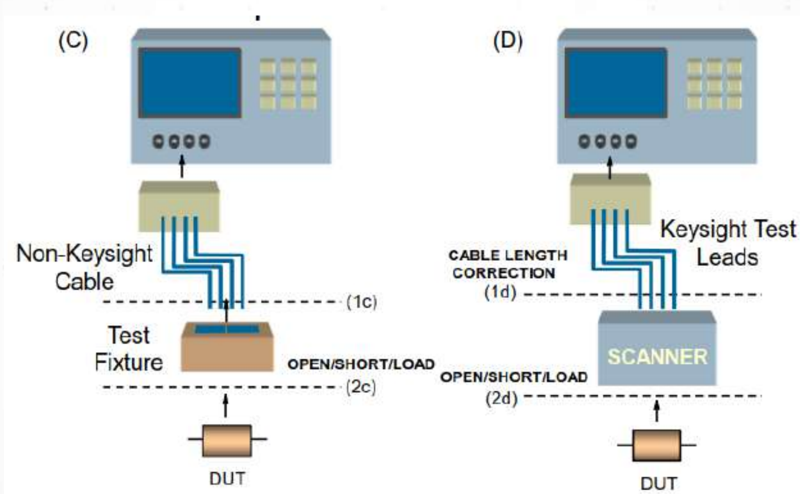
治具補償

Which compensation technique should you use?
- Selection Guideline -



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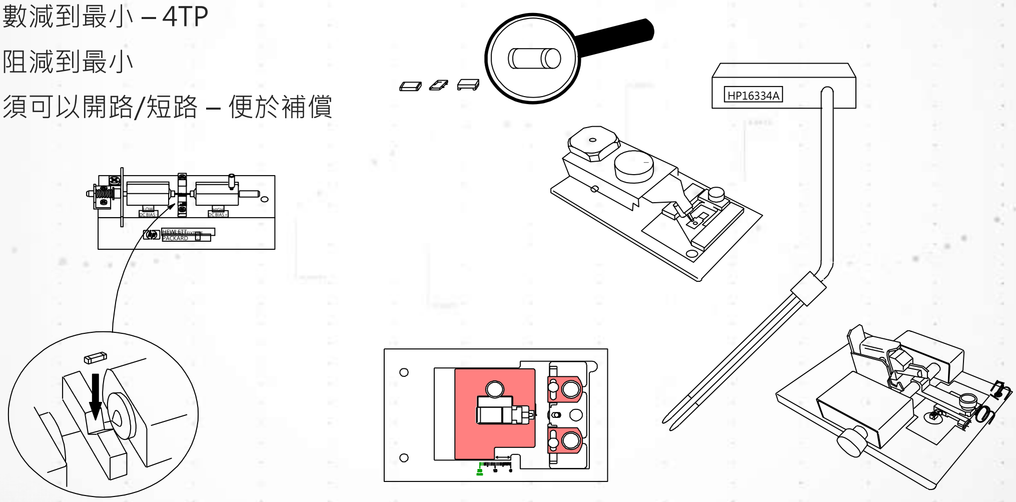
測試夾具製作需求

基本要求

- 殘餘參數減到最小 – 4TP
- 接觸電阻減到最小
- 接觸必須可以開路/短路 – 便於補償



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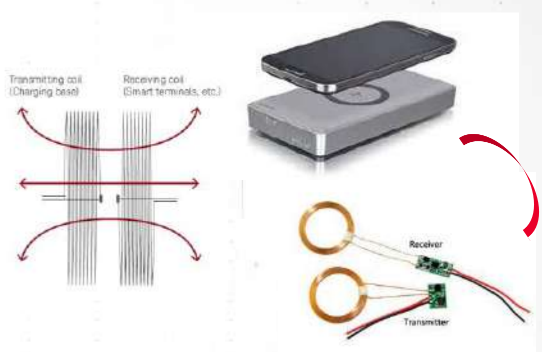
元件阻抗的精密測試

線圈

- 線圈中的 LC 諧振電路會直接影響功率傳輸效率，因此需要用阻抗、電感、電容和 Q 因數 仔細地進行表徵
- 對於高對於高效率的無線充電設計來說，更低的損耗（低 DCR）和寄生（高 Q）是必不可少的效率的無線充電設計來說，更低的損耗（低 DCR）和寄生（高 Q）是必不可少的。



待測物指標舉例:
L = 9.5 - 10.2 uH
Rs = 595 - 640 mOhm @ 128 kHz

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元件阻抗的精確測試

高精準度的標準 DCR 量測

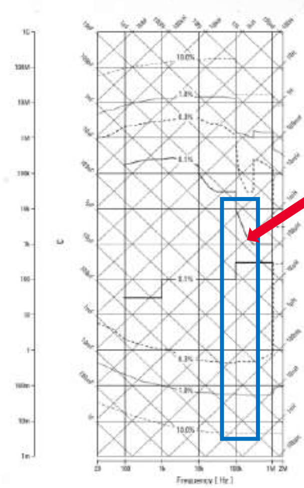
- 發射機線圈和接收機線圈的 直流電阻會直接影響能量傳輸的電阻損耗，因此需要更低的 DCR（通常低到毫歐級）來確保更高的功率傳輸效率。

- DCR （直流電阻） 量測是 E4980A/AL 精密 LCR 表的標配功能。
- E4980A/AL 能非常精確地量測低到毫歐級的 DCR 值。同時，E4980A/AL 支持低接觸電阻夾具，如 16047E 和夾具補償功能。
- 如果線圈的 DCR 是 100 毫歐，E4980A/AL 的 DCR 精準度可達 5%，意味著真值在大約 95 毫歐到 105 毫歐之間。

元件阻抗的精確測試

高精準度的電感量測

- 發射機和接收機線圈的電感通常在微亨 μH 範圍，測試在幾十到數百kHz的頻率範圍內進行。因此，阻抗範圍從幾毫歐到幾歐。
- E4980A/AL LCR 表具有優異的寬阻抗範圍性能，可保持 10% 以內 的精準度，特別適合於無線充電系統線圈的量測。



無線充電線圈的典型阻抗範圍和頻率範圍

元件阻抗的精確測試

穩定量測電感的等效串聯電阻(ESR)

- 為了滿足低功耗要求，線圈電感的等效串聯電阻（ESR）也要儘量低。
- E4980A 提供穩定的低 ESR量測

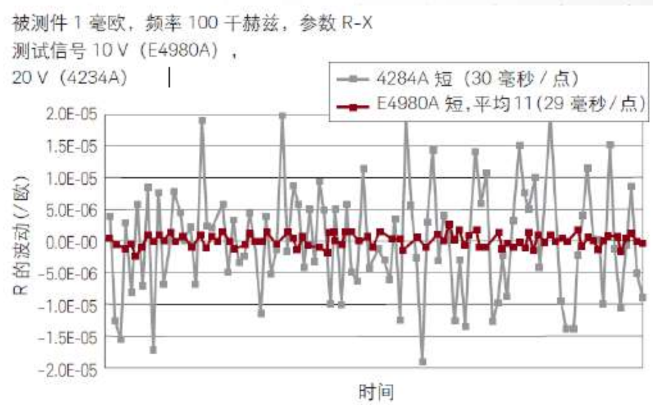


图 3. 低阻抗评估（E4980A， 1 毫欧 100K 赫兹）

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Thank You !

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