



Agilent 428X系列LCR表

用户培训



Agilent Technologies

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- 手机：13601839398
- 电子邮件：haiyang_hu@agilent.com
- 技术支持热线：800-810-0189

- 时间安排：
 - 9:00~11:00
 - 1:30~4:00



428X系列LCR表

- 4284A 精密LCR表 (20 Hz to 1 MHz; 10m~100M Ω)
- 4285A 通用精密LCR表 (75 kHz to 30 MHz; 10m~100M Ω)
- 4288A 电容表 (1 kHz/1 MHz; 1m~100M Ω)
- 4287A RF LCR表 (1 MHz to 3 GHz; 200m~3k Ω)



内容安排

- 阻抗测量原理
- **4284A/4285A/4288A LCR表介绍**
- **4287A RF LCR表介绍**



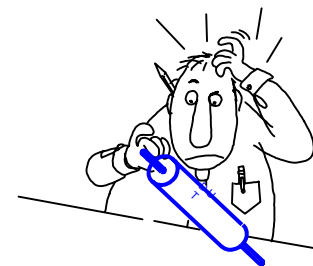
1. 阻抗测量基础

- 阻抗基础
- 阻抗测量方法
- 夹具和电缆连接
- 校准和补偿



LCR与阻抗

- 为什么叫**LCR**表?
- **LCR**和阻抗的关系是什么?
- 阻抗和导纳的关系是什么?
- 什么是品质因子**Q**? 什么是损耗因子**D**?
- 为什么要测阻抗?



什么是阻抗?

- 矢量
- 交流测试信号
- 阻抗的单位: Ω 欧姆

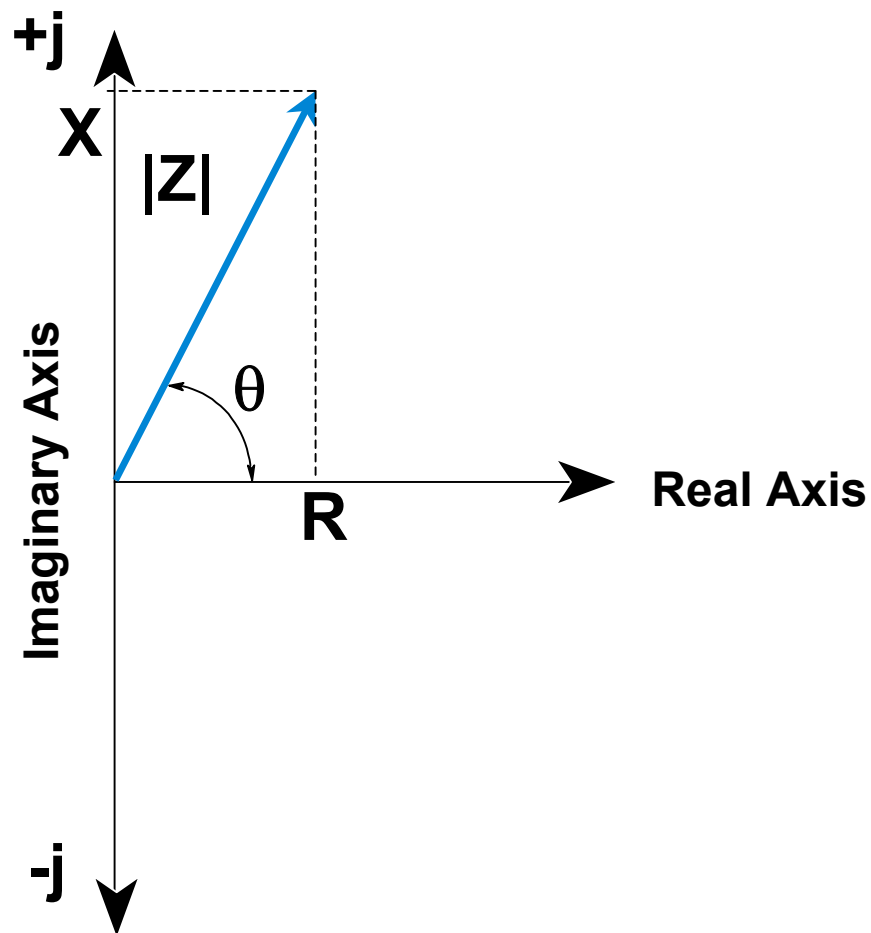
$$\mathbf{Z} = \mathbf{R} + \mathbf{jX} = |\mathbf{Z}| \angle \theta$$

$$|\mathbf{Z}| = \sqrt{\mathbf{R}^2 + \mathbf{X}^2}$$

$$\theta = \tan^{-1}\left(\frac{\mathbf{X}}{\mathbf{R}}\right)$$

$$\mathbf{R} = |\mathbf{Z}| \cos\theta$$

$$\mathbf{X} = |\mathbf{Z}| \sin\theta$$



什么是导纳?

$$Y = \frac{1}{Z}$$

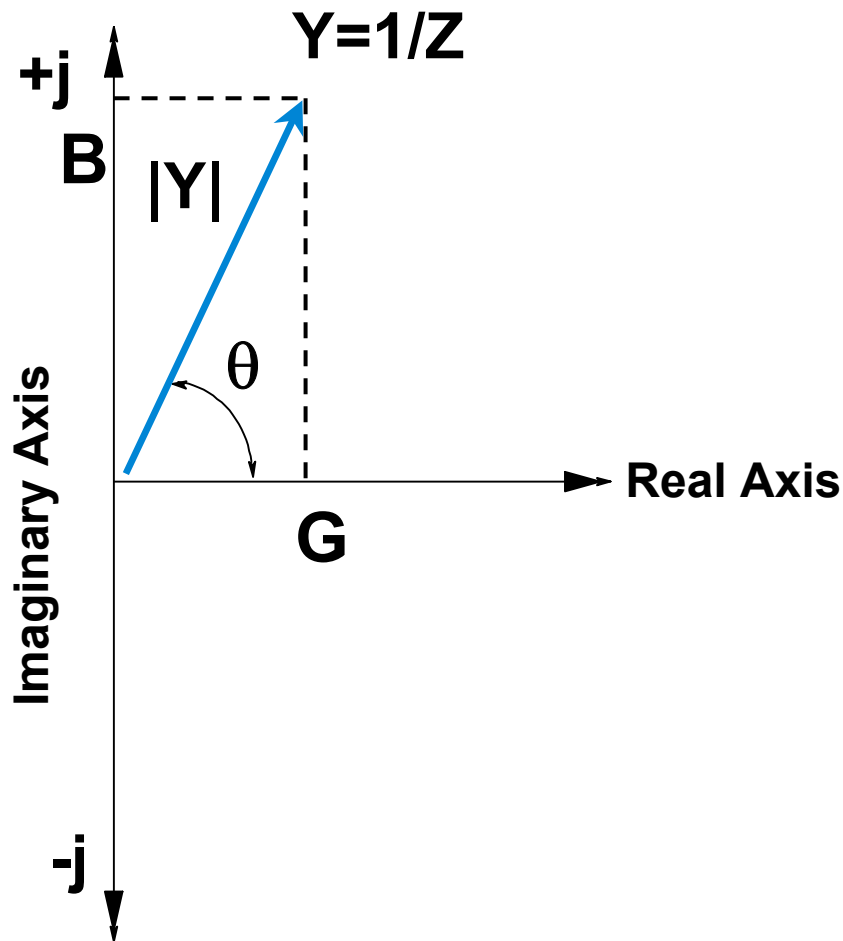
$$Y = G + jB = |Y| \angle \theta$$

$$|Y| = \sqrt{G^2 + B^2}$$

$$\theta = \tan^{-1}\left(\frac{B}{G}\right)$$

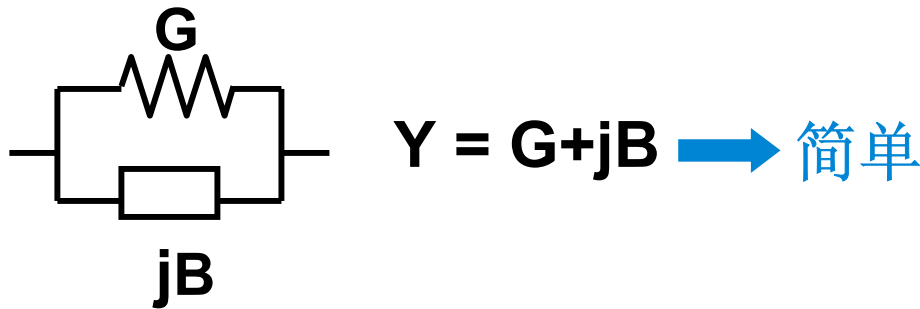
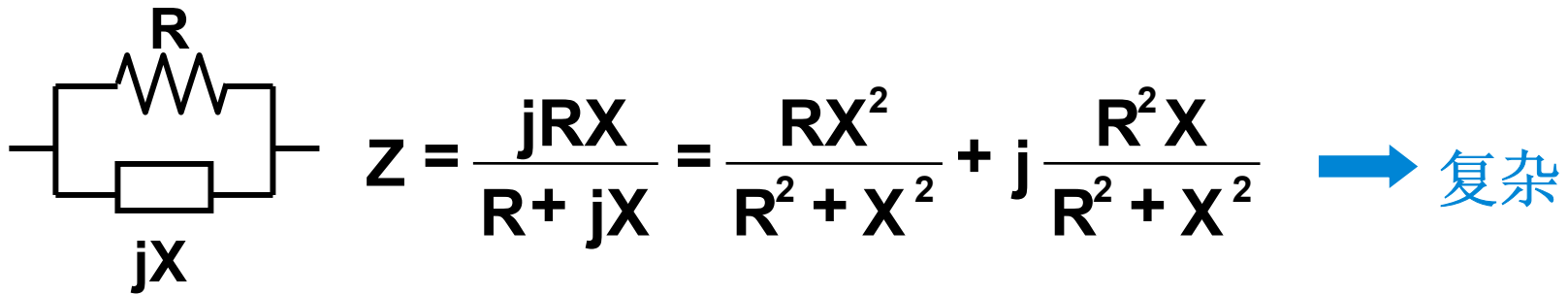
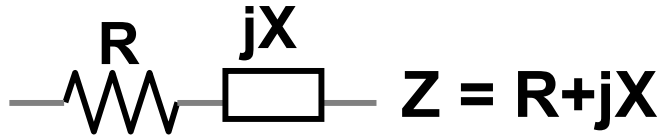
$$G = |Y| \cos \theta$$

$$B = |Y| \sin \theta$$



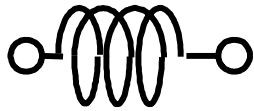
导纳的单位: **Siemen** 西门子

阻抗和导纳



阻抗同电感L和电容C的关系

- 理想电感



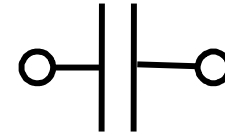
L 单位: H

$$|Z| = |X_L| = 2\pi fL$$

$$= \omega L$$

$$Z = j \omega L$$

- 理想电容



C 单位: F

$$|Z| = |X_c| = 1/(2\pi fC)$$

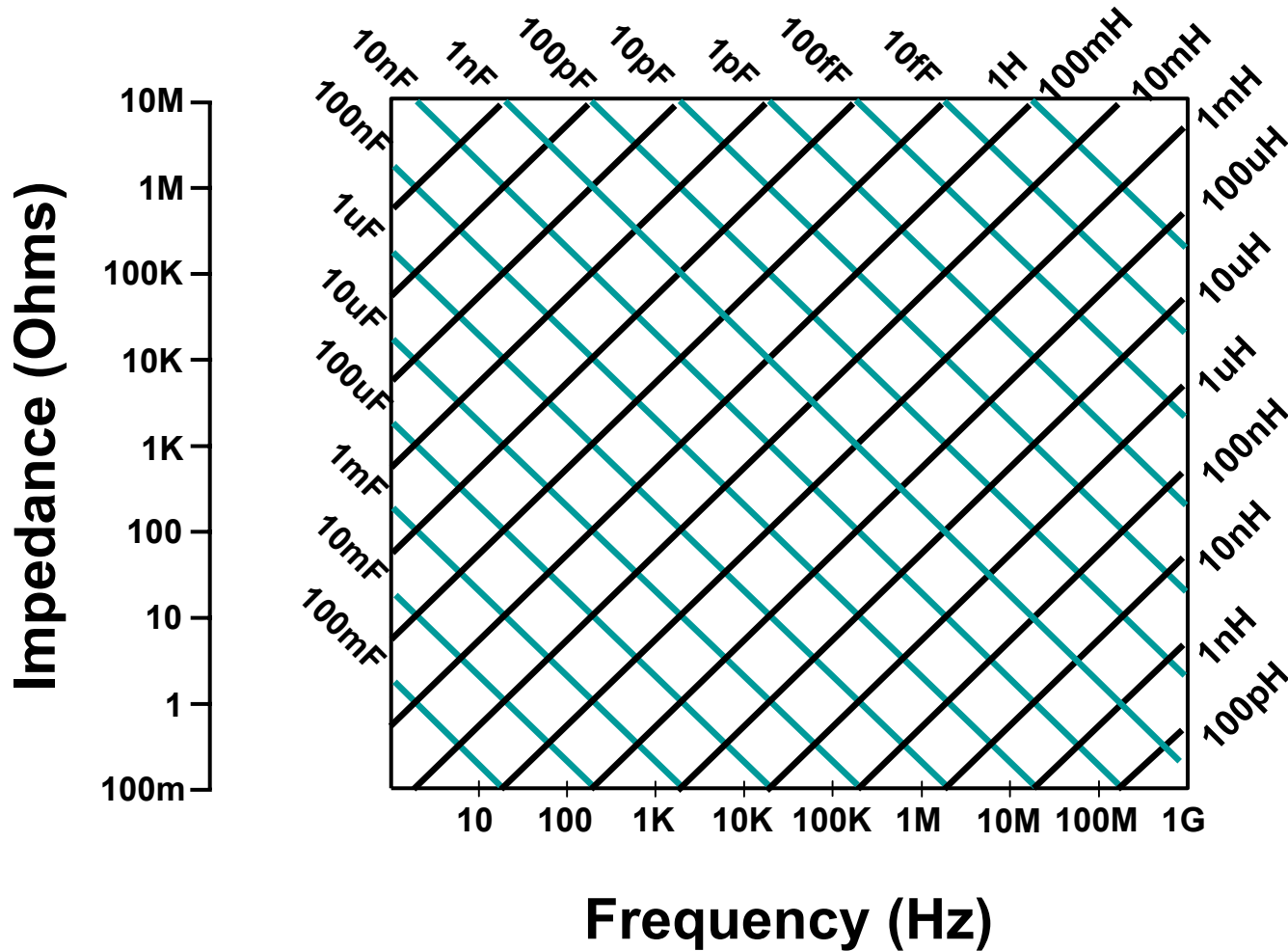
$$= 1/(\omega C)$$

$$Z = 1/(j\omega C) = -j/(\omega C)$$

$$Z = R + jX$$



阻抗 vs. 频率 (电感和电容)



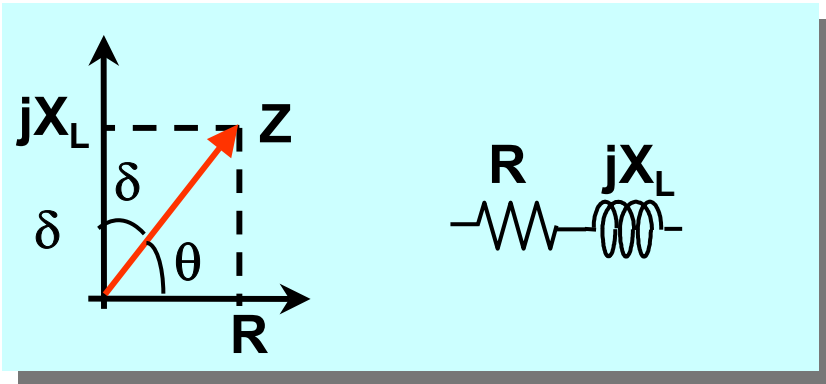
For C:
 $|Z| = 1/(2\pi fC)$

For L:
 $|Z| = 2\pi fL$

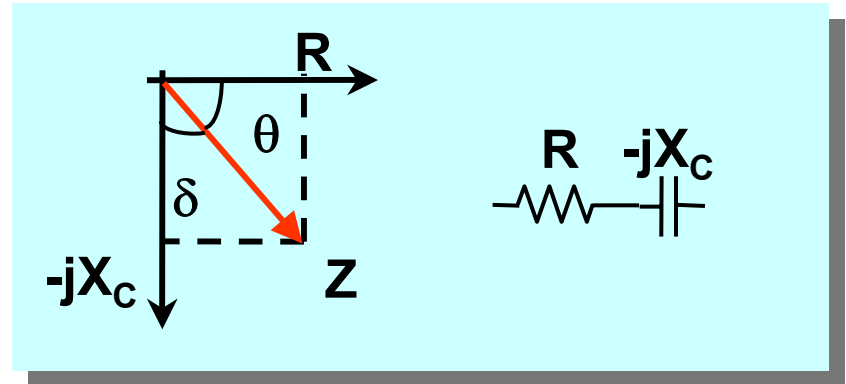


阻抗和导纳之间的关系

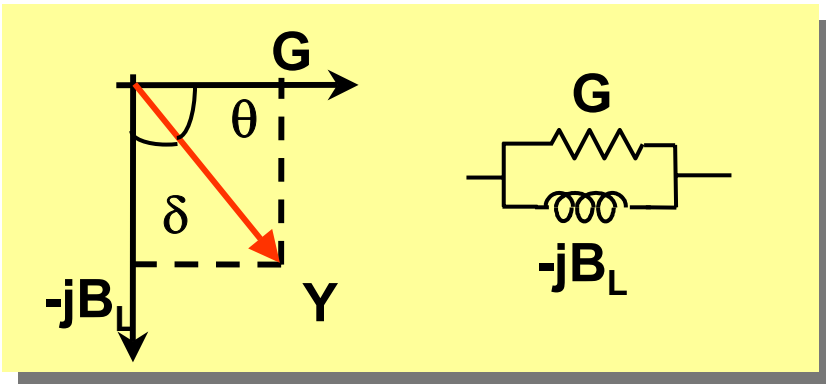
1. 感性矢量 (阻抗)



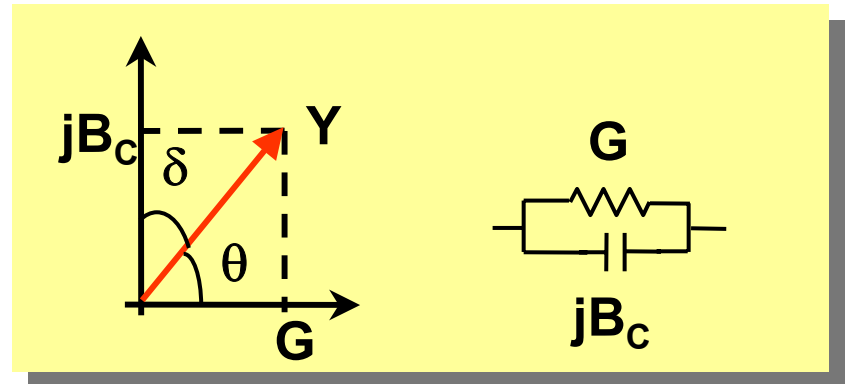
2. 容性矢量 (阻抗)



3. 感性矢量 (导纳)



4. 容性矢量 (导纳)



品质因子Q和损耗因子 D

- $Q = X/R = (\text{储备能量})/(\text{损失能量})$
- $D = 1/Q$ (主要针对电容)

$$Q = \frac{1}{D} = \frac{1}{\tan\delta} = \frac{X_L}{R} = -\frac{X_C}{R} = \frac{B_L}{G} = \frac{B_C}{G}$$

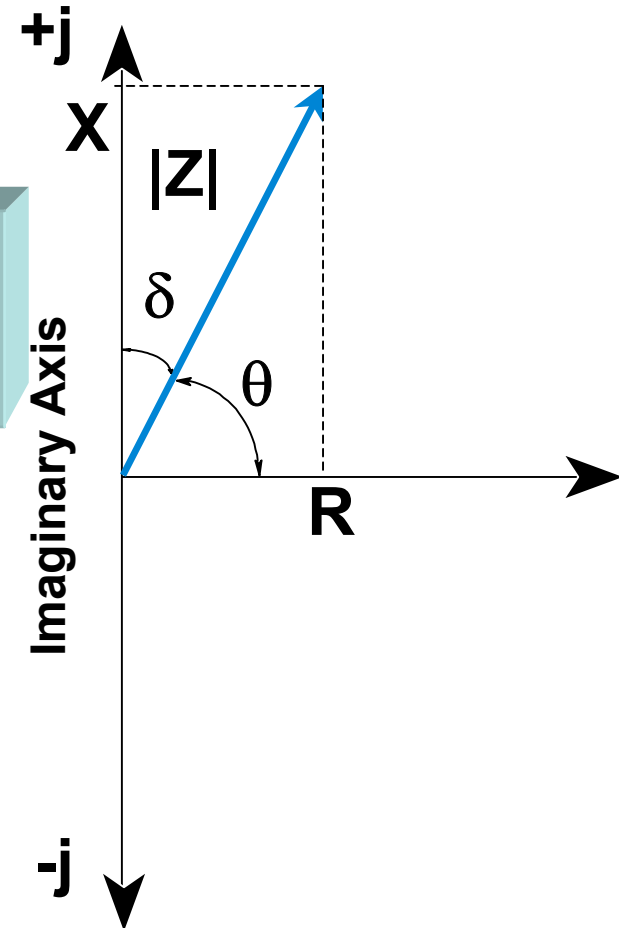
原件越好, $R \rightarrow 0$



$Q \rightarrow \infty$ $D \rightarrow 0$

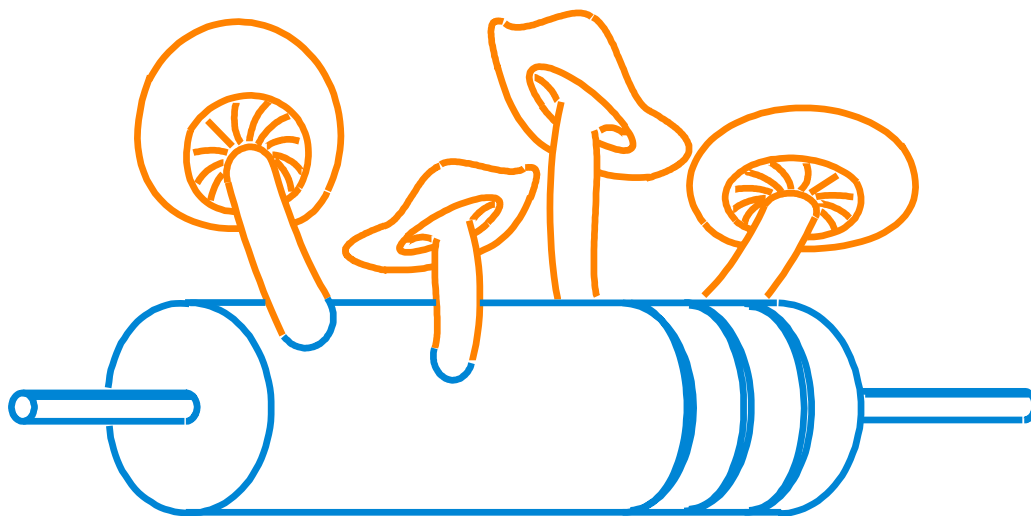
$$Z = R + jX_c$$

$$Y = G + jB$$



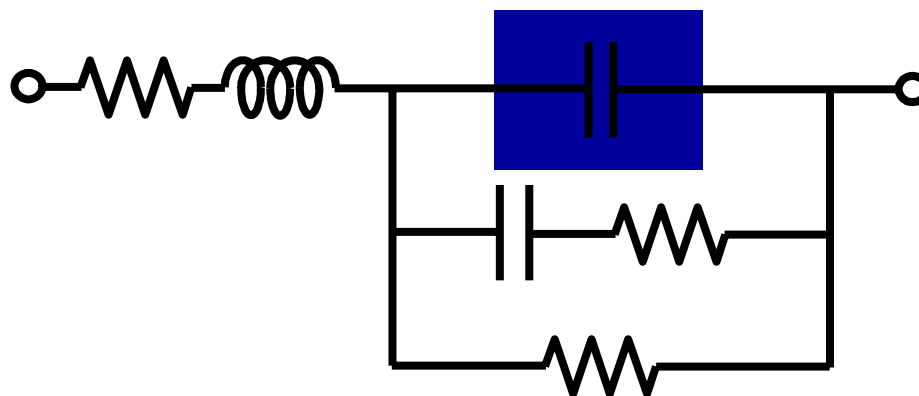
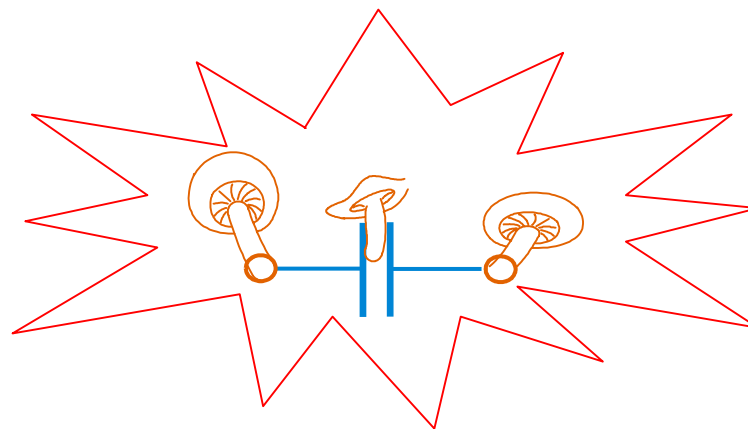
为什么我们要测试阻抗？

- 电子器件的寄生参数



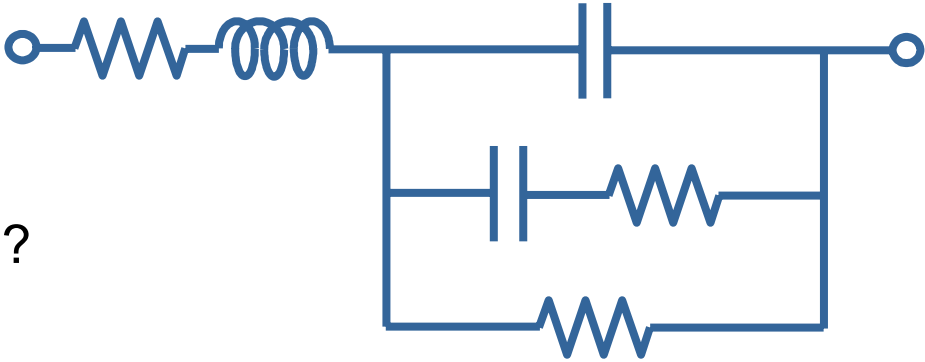
实际电容模型

- 包含寄生参数



如何选择电路模型？

电容模型
 R_s, L_s, R_p, C_p ?



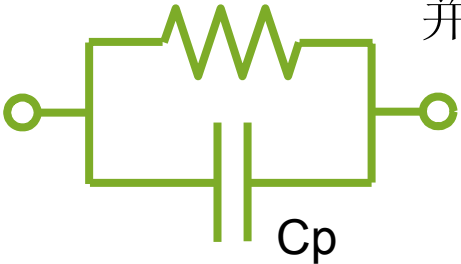
串联模型



低阻抗器件 $Z < 10\Omega$
大电容C, 小电感L

R_p

并联模型

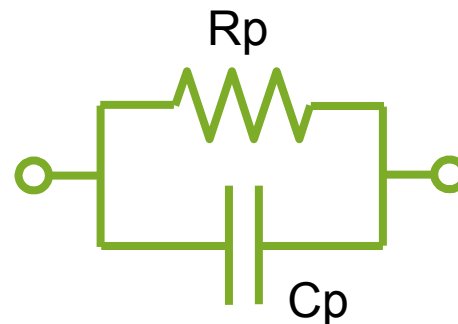


高阻抗器件 $Z > 10k\Omega$
小电容C, 大电感L

哪一个模型正确？



Series model



Parallel model

- 两种都正确
 $C_S = C_P (1 + D^2)$
- 在特定情况下，其中一种更近似反映实际情况
- 对于高Q 或者低D 的器件, $C_S \approx C_P$



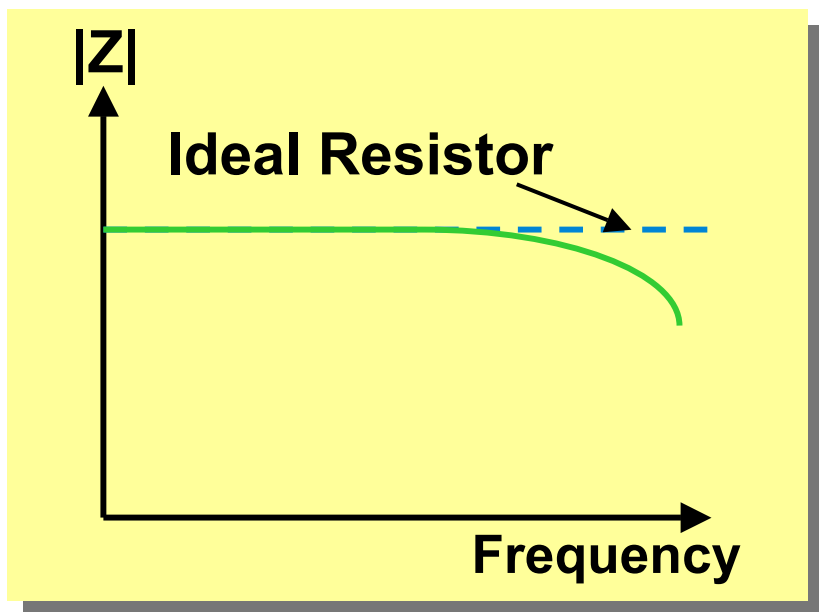
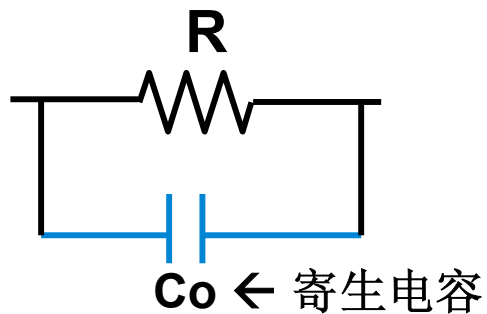
为什么我们要测试阻抗？

- 元件的阻抗受很多因素影响
 - 频率
 - 测试信号
 - 直流偏置
 - 温度
 - 其他

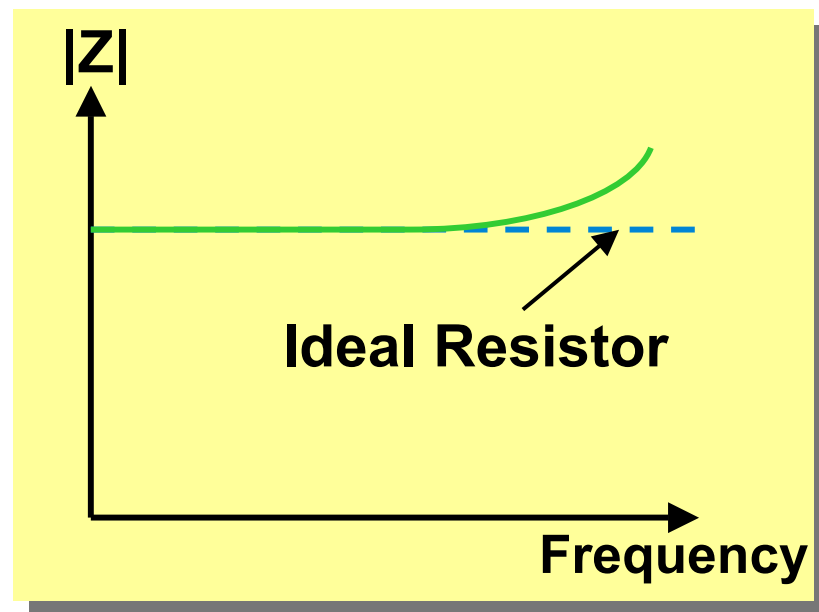
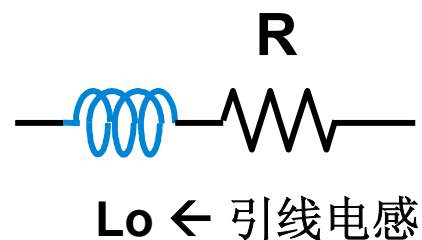


频率 (电阻)

1. 高阻值电阻

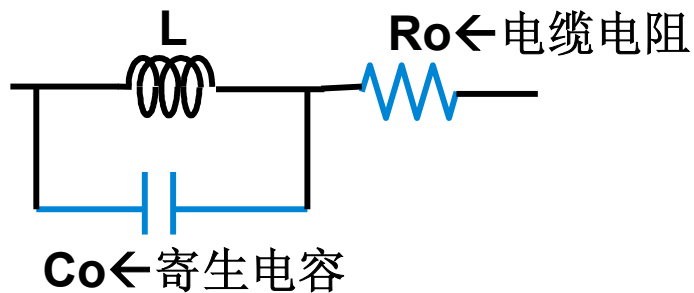


2. 低阻值电阻

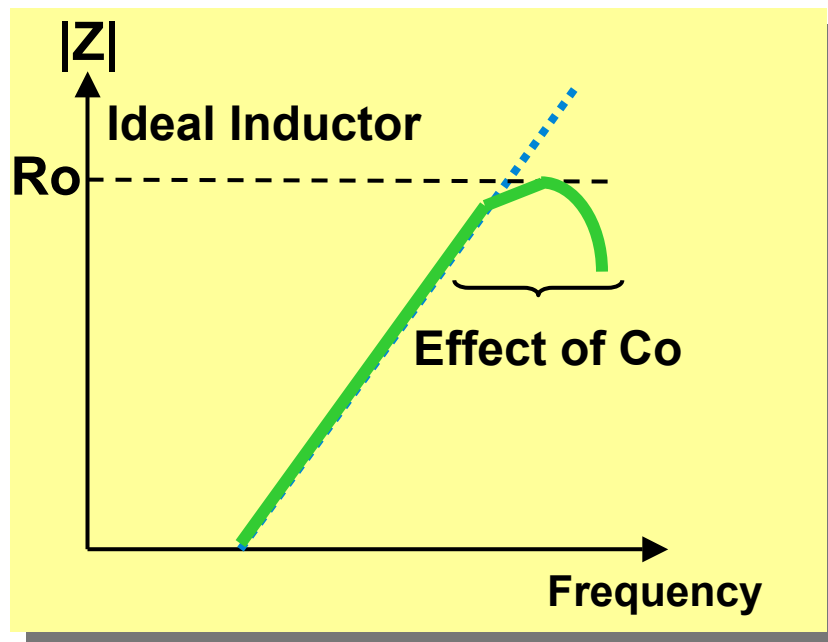
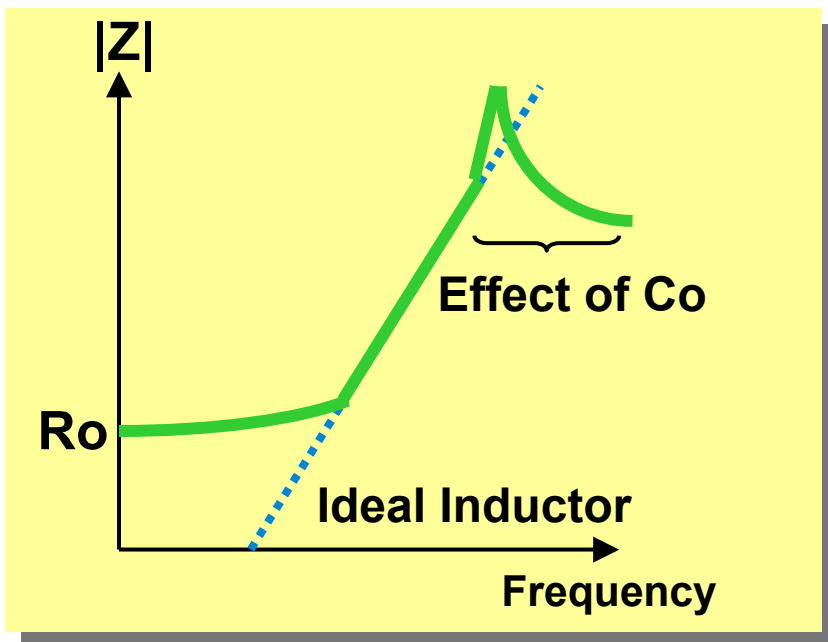
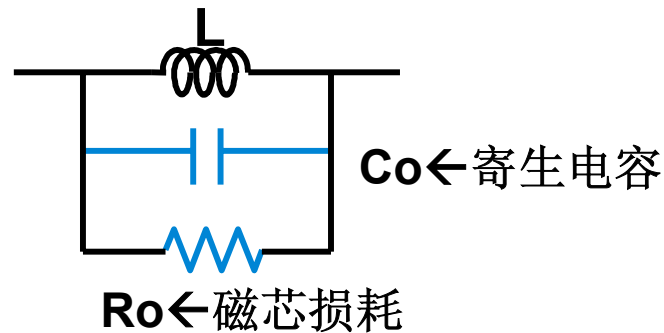


频率 (电感)

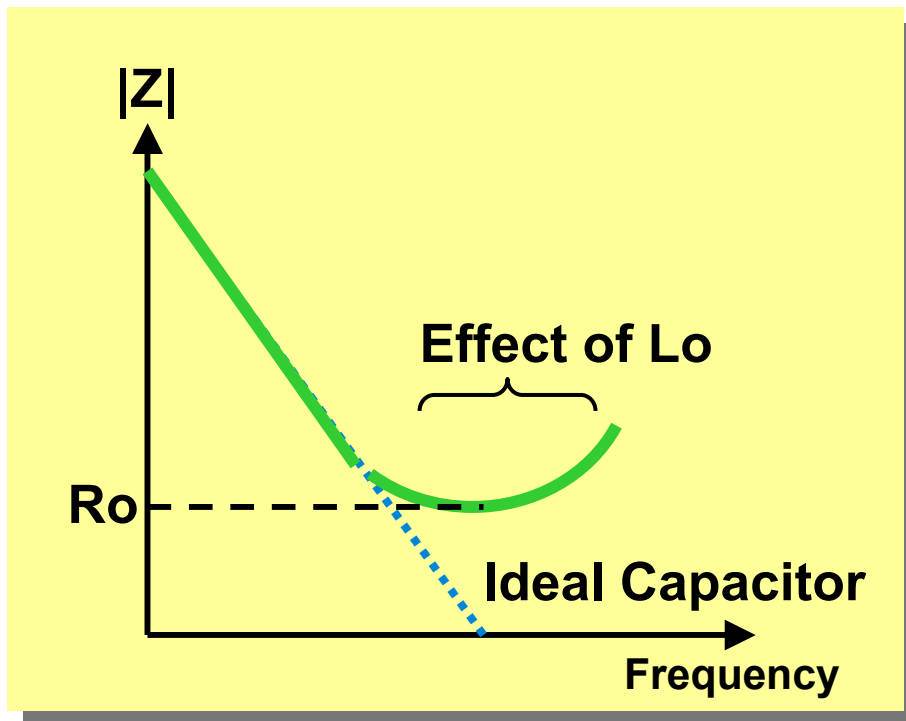
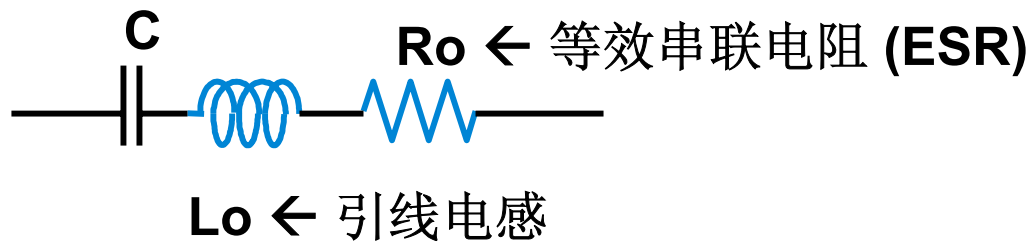
• 1. 普通电感



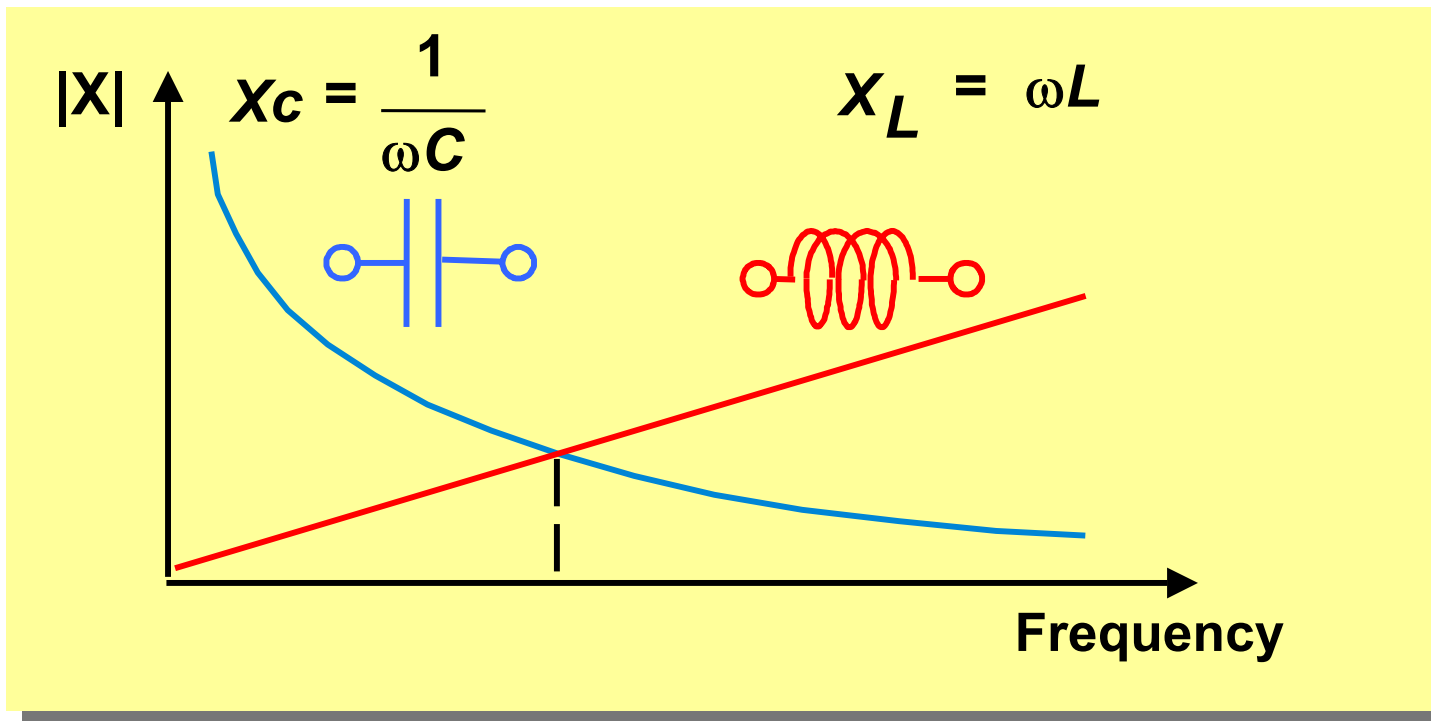
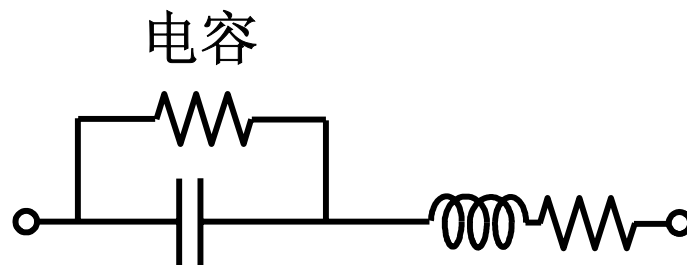
• 2. 高磁芯损耗的电感



频率 (电容)

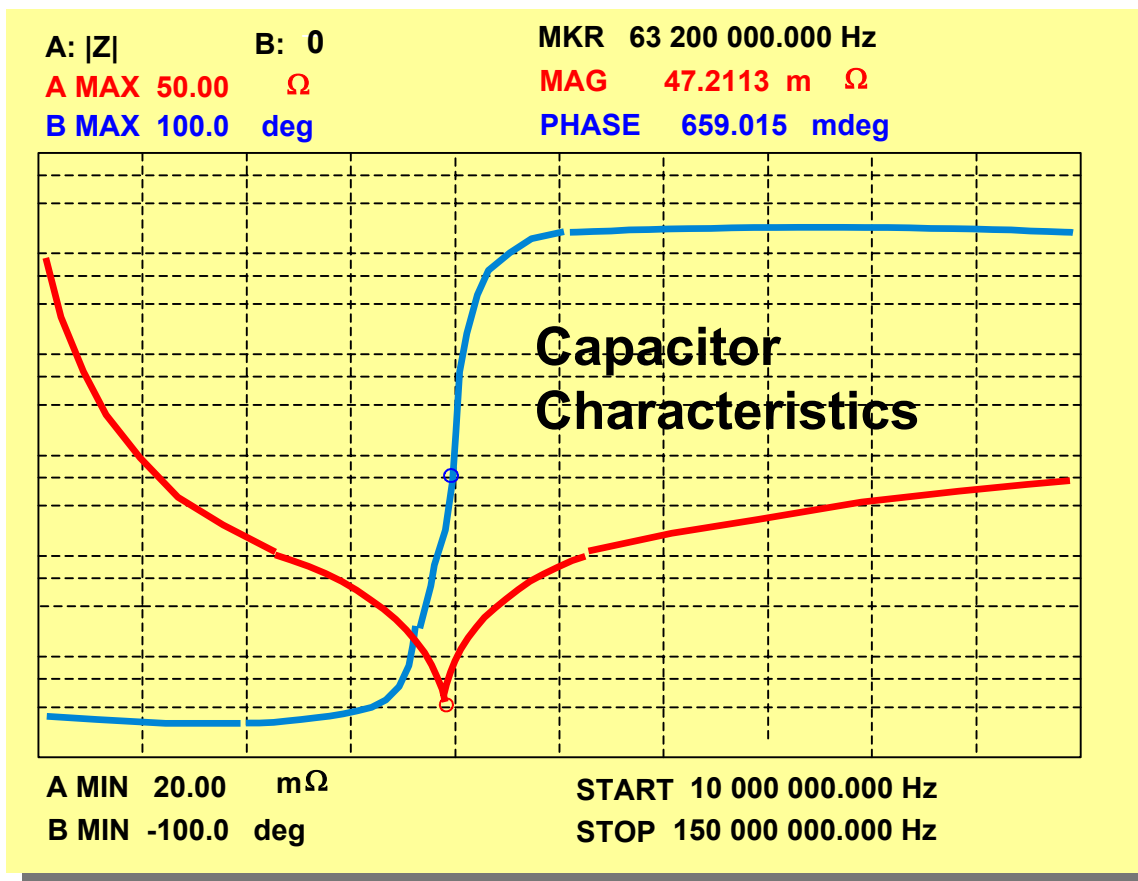


频率和电抗



阻抗测量例子

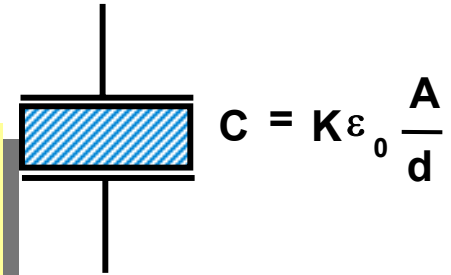
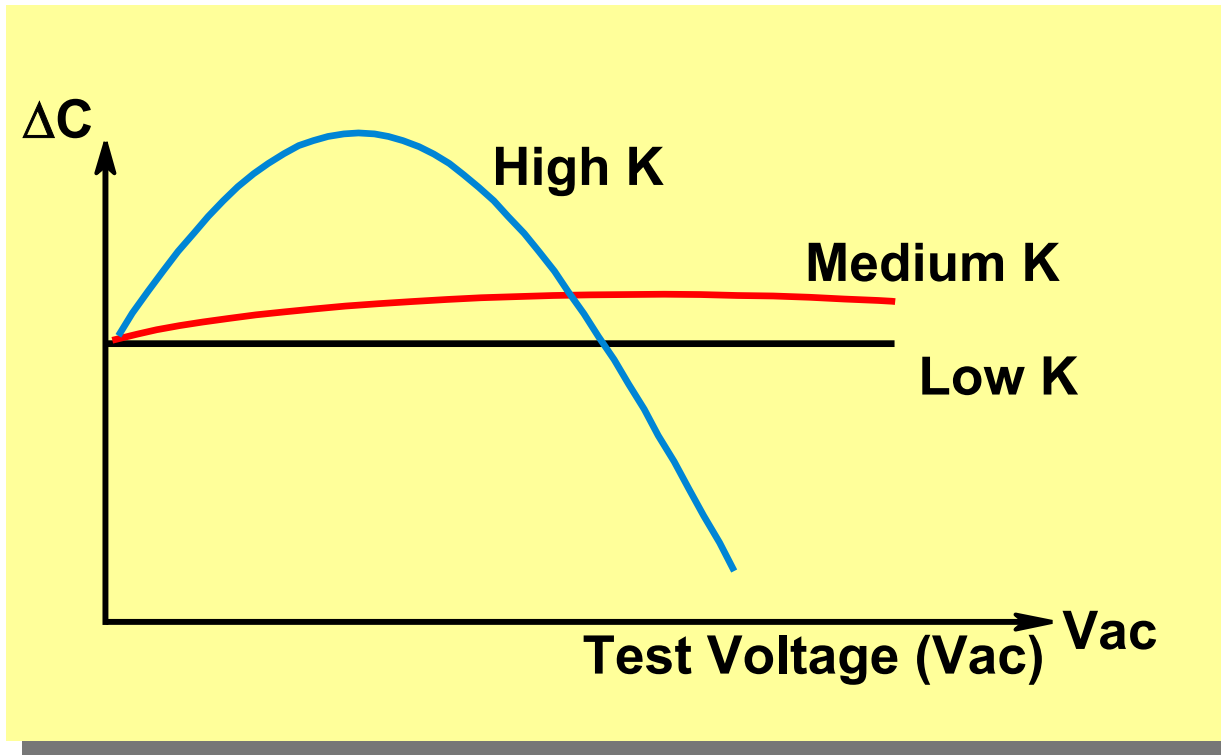
- 谐振频率



交流信号电平的影响 (电容)

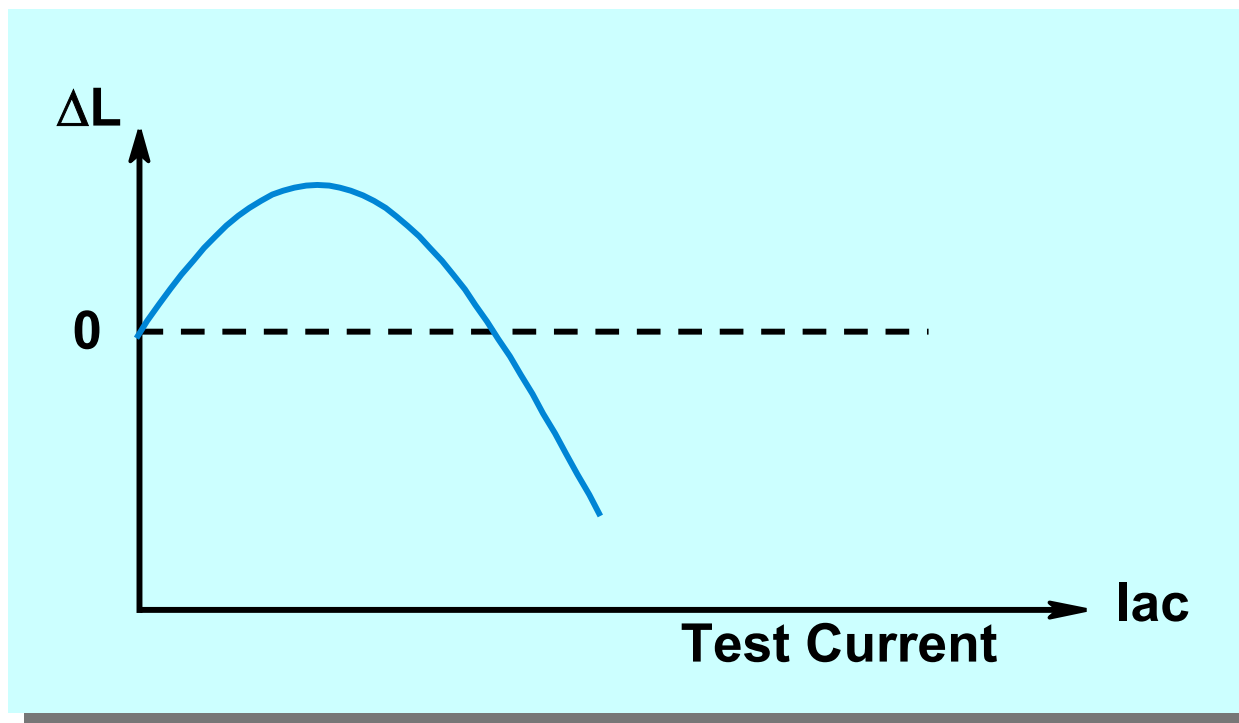
- 与交流电压有关的**SMD** 电容 (具有不同的介电常数, **K**)

表面封装器件



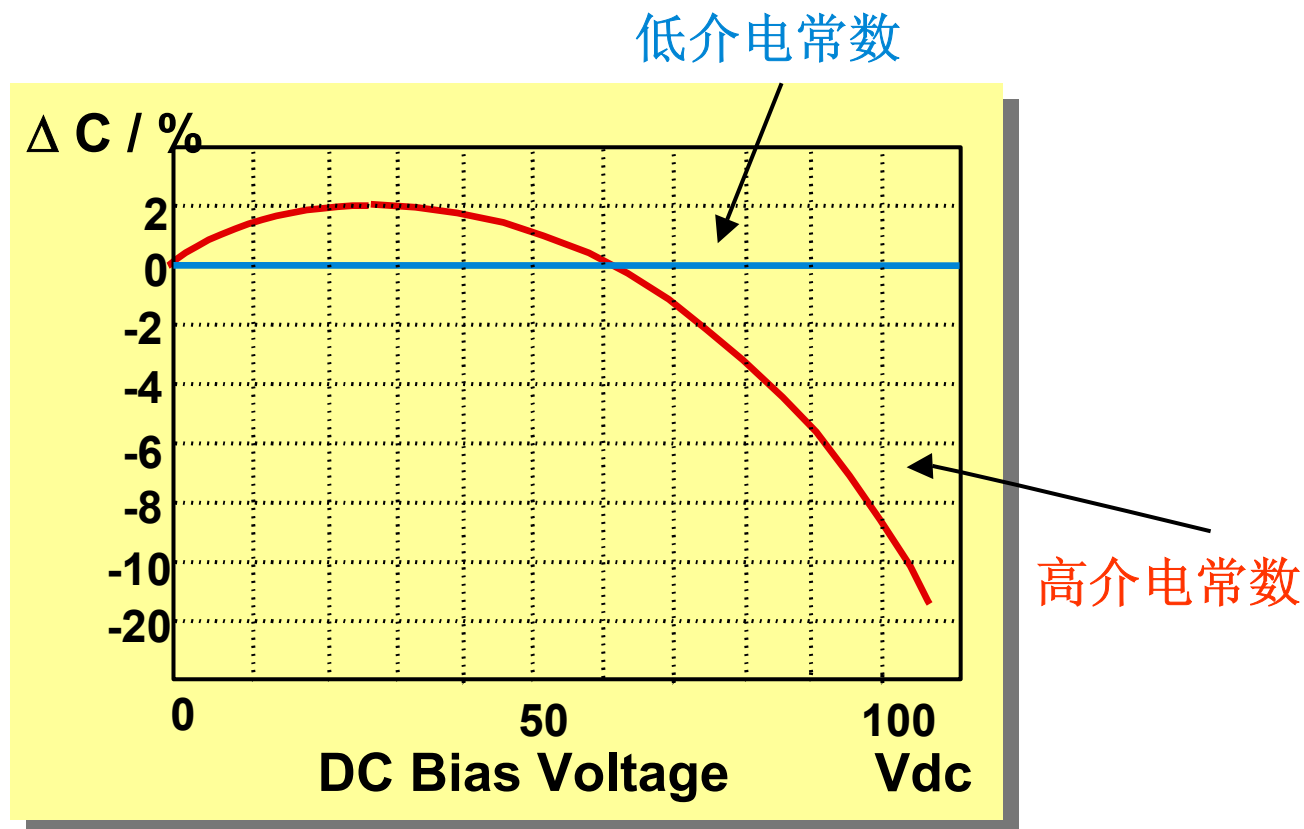
交流信号电流的影响（电感）

- 与交流电流有关的磁芯电感器



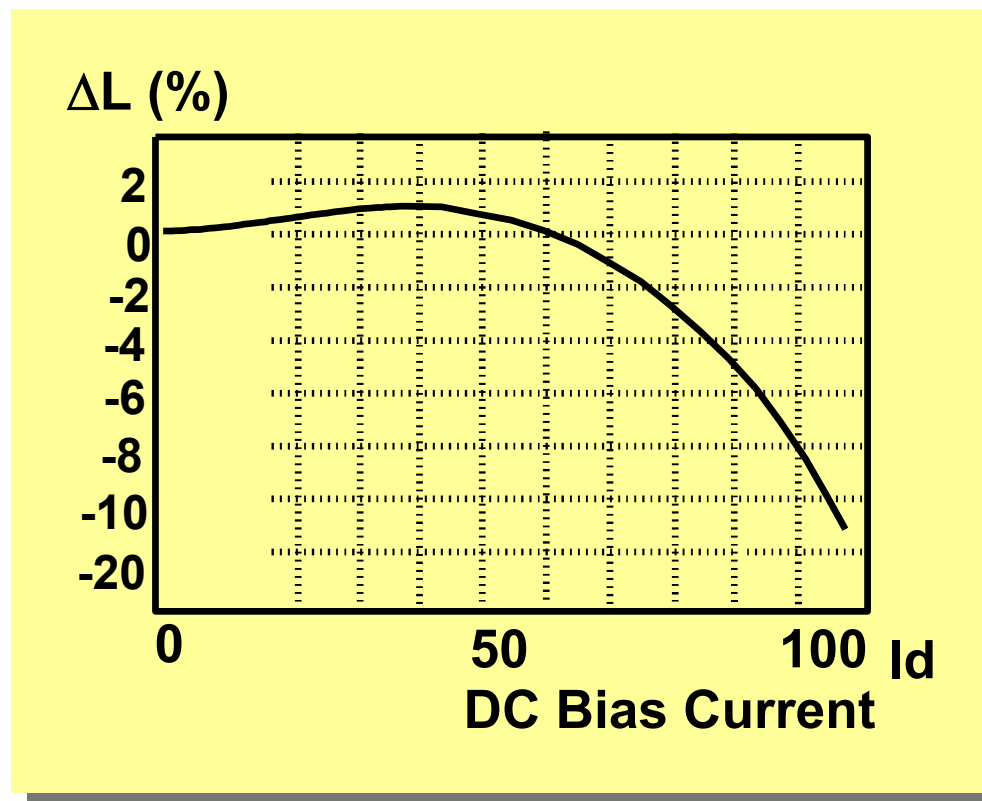
直流偏置电平的影响（电容）

- 陶瓷电容

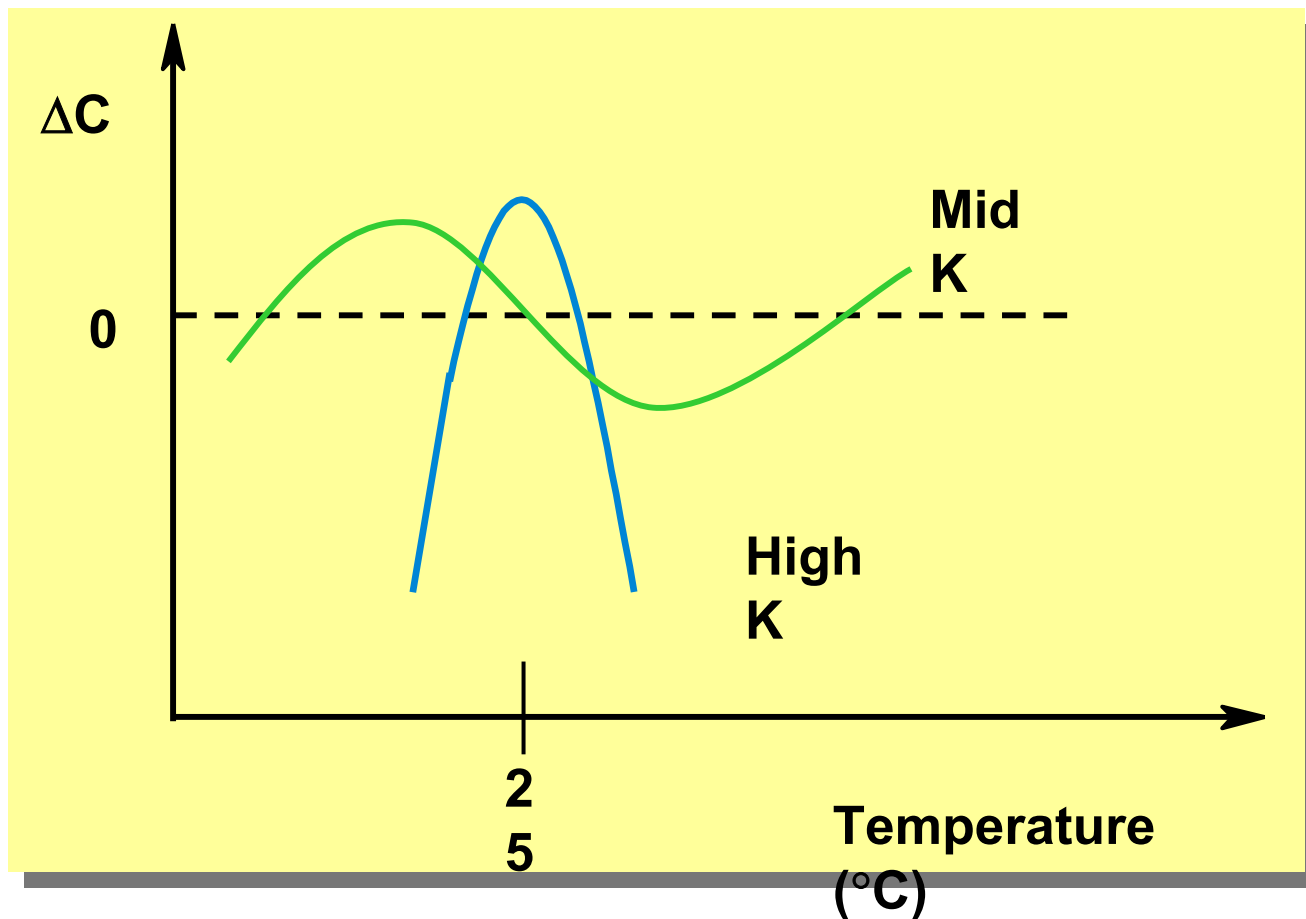


直流偏置电流的影响（电感）

- 磁芯电感器

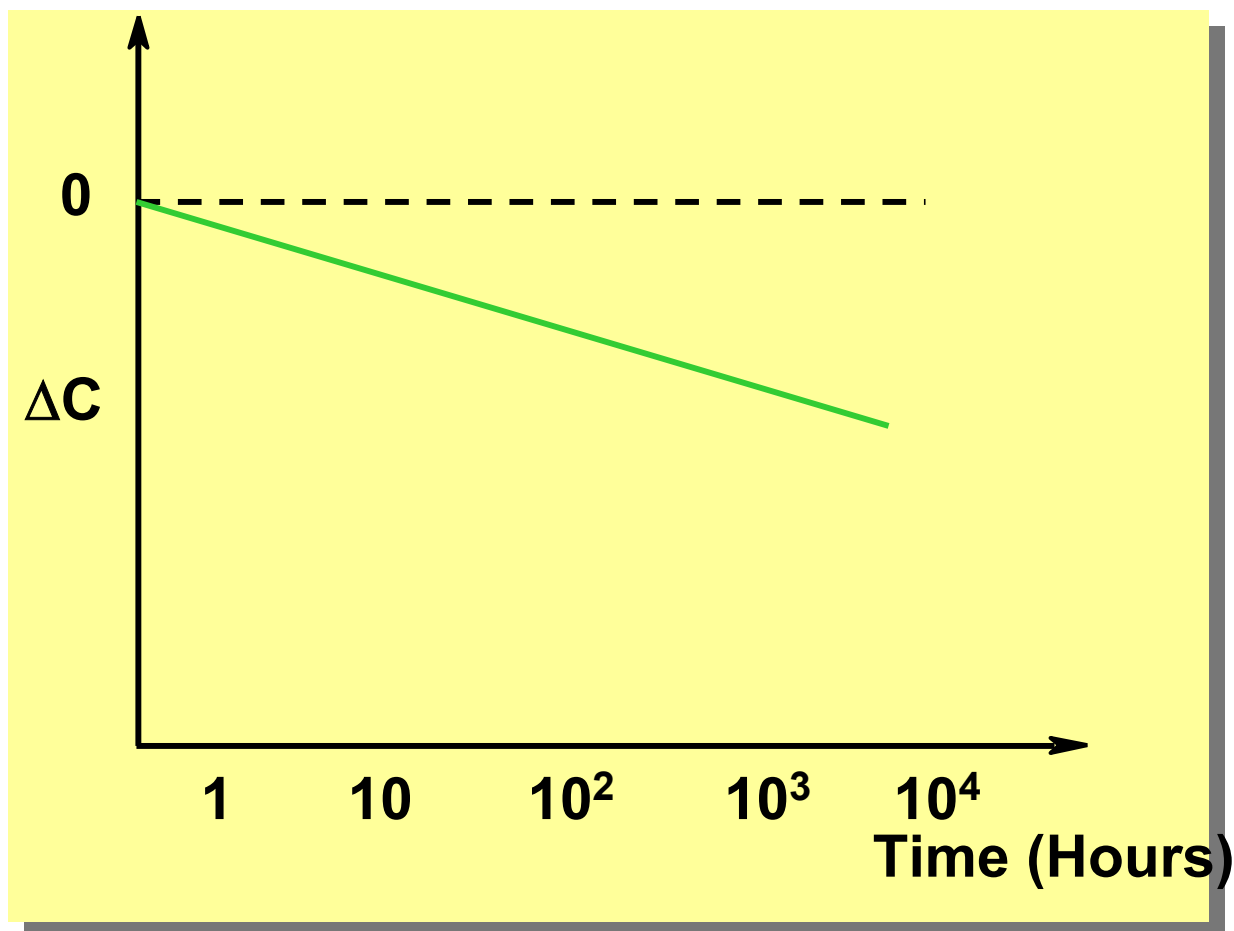


温度相关性 (陶瓷电容)



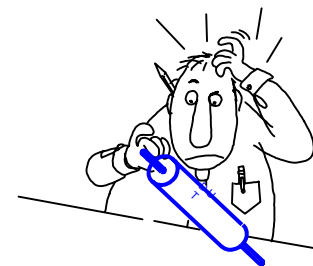
其它影响因素（老化）

- 陶瓷电容的老化相关性



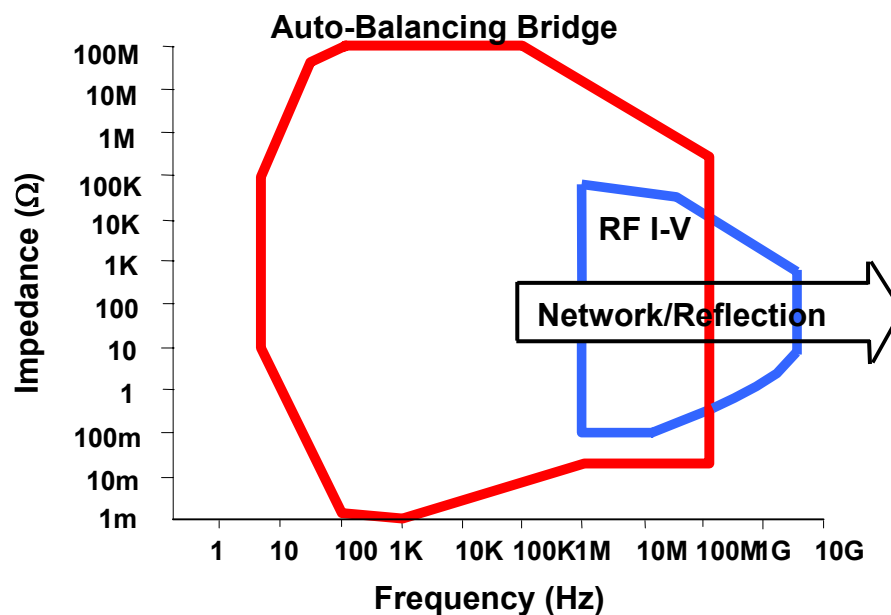
LCR与阻抗

- 为什么叫**LCR**表?
- **LCR**和阻抗的关系是什么?
- 阻抗和导纳的关系是什么?
- 什么是品质因子**Q**? 什么是损耗因子**D**?
- 为什么要测阻抗?

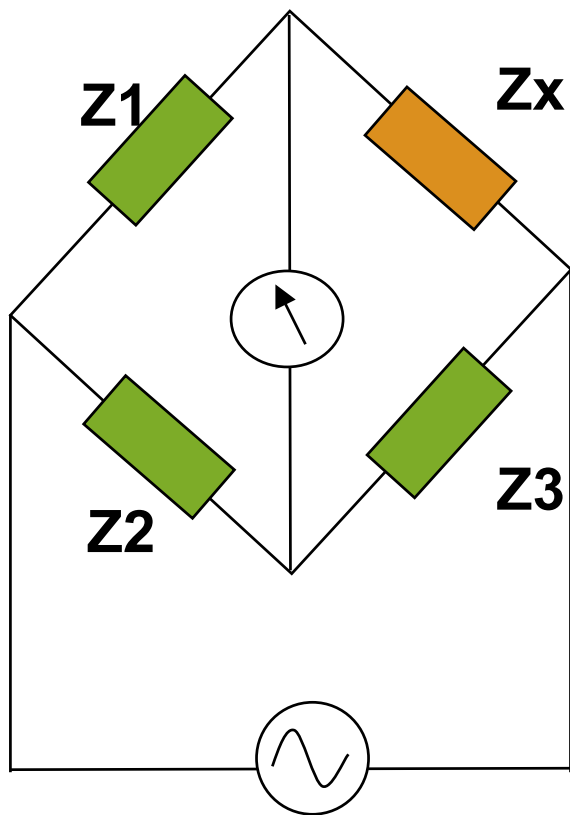


1. 阻抗测量基础

- 阻抗基础
- 阻抗测量方法
- 夹具和电缆连接
- 校准和补偿
- 总结



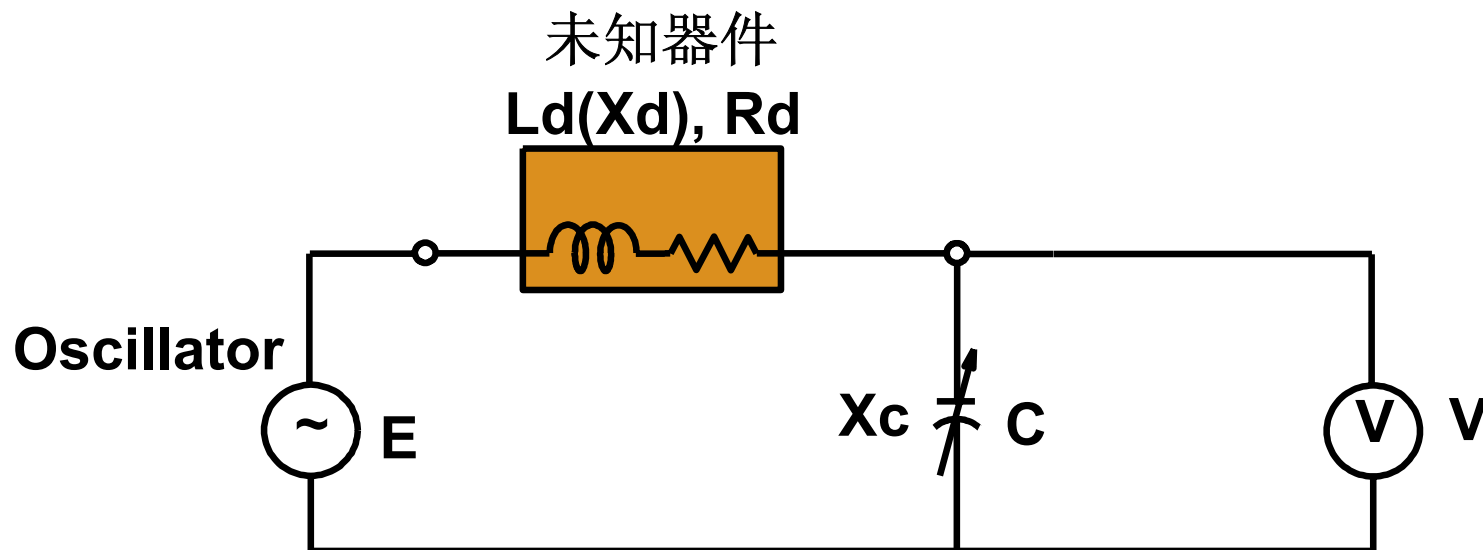
电桥法



$$Z_x = \frac{Z_1}{Z_2} Z_3$$



谐振法 (Q Meter)



$$X_c = \frac{V}{I} = \frac{V}{E/R_d} = \frac{R_d V}{E}$$

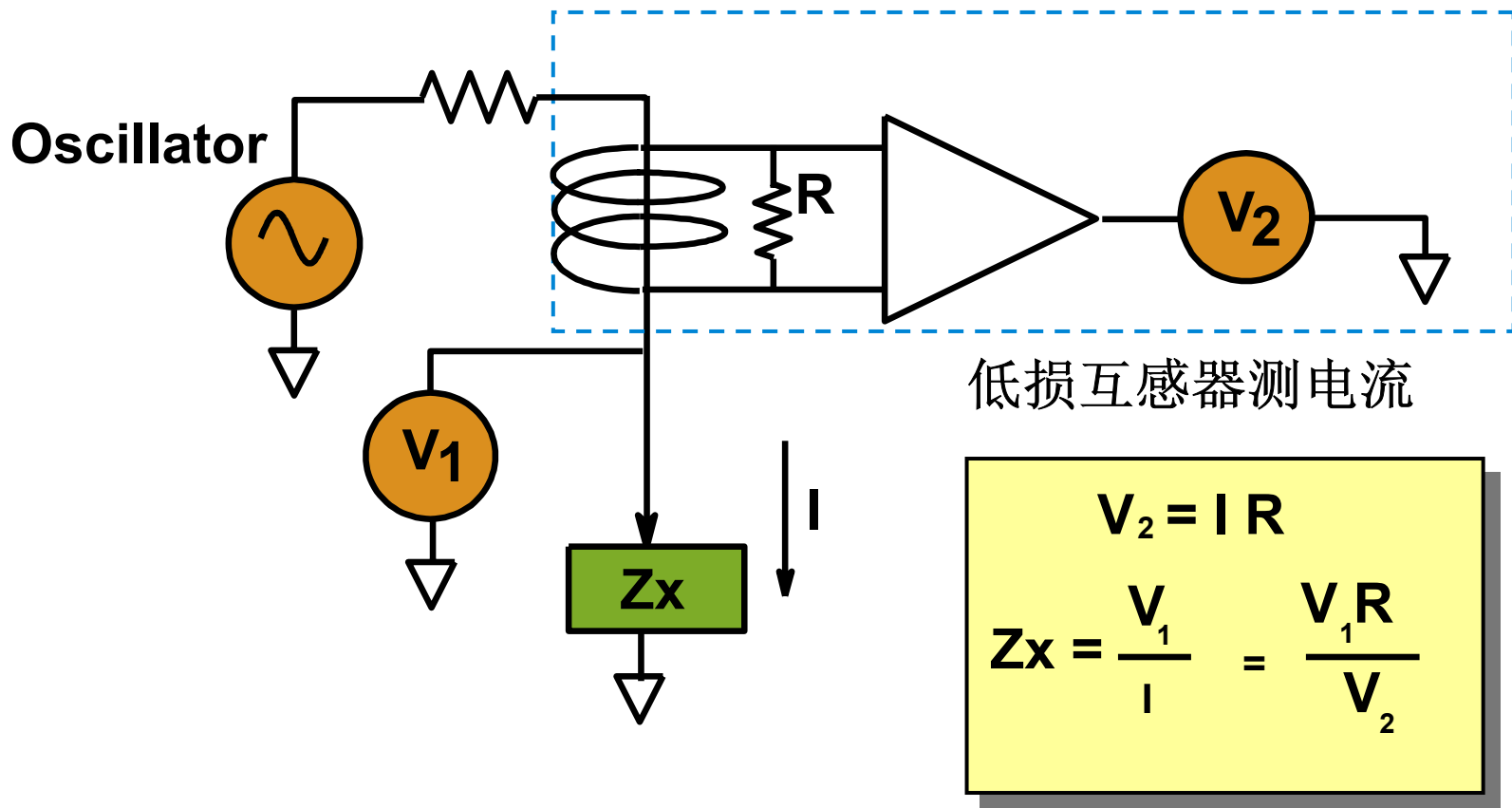
$$Q = \frac{|X_d|}{R_d} = \frac{|X_c|}{R_d} = \frac{|V|}{E}$$

1. 调谐电容**C**使达到谐振
2. 谐振条件: **Xd=-Xc**

由于测量电路损耗很低, 因此可以测量高大**1000**的**Q**



I-V法 (Probe)



I-V 法测量阻抗产品



+



HP 42941A Impedance Probe Kit

**Agilent 4294A with
42941A Impedance
Probe Kit**



+



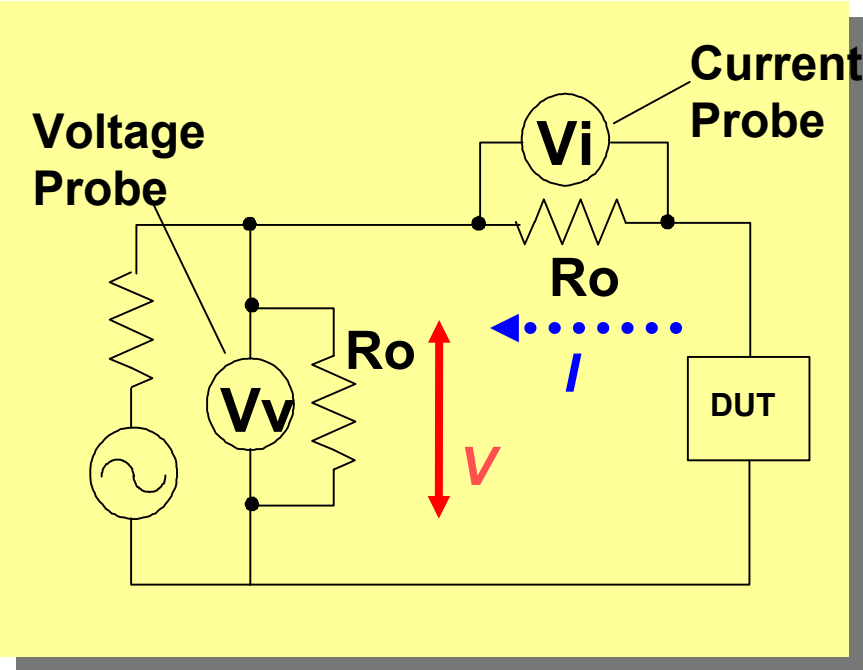
HP 41941B Impedance Probe Kit

**Agilent 4194A with
41941B Impedance
Probe Kit**

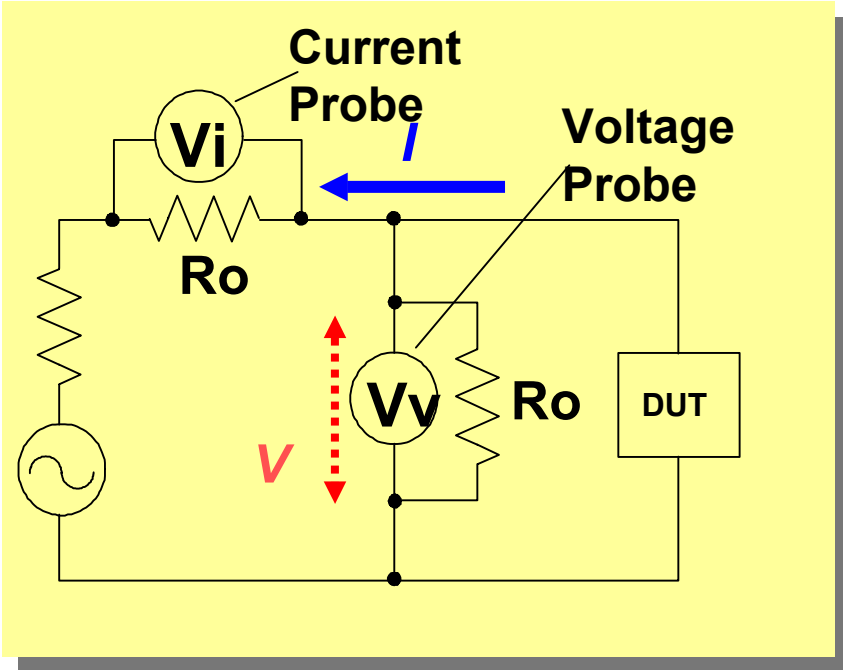


射频 I-V法

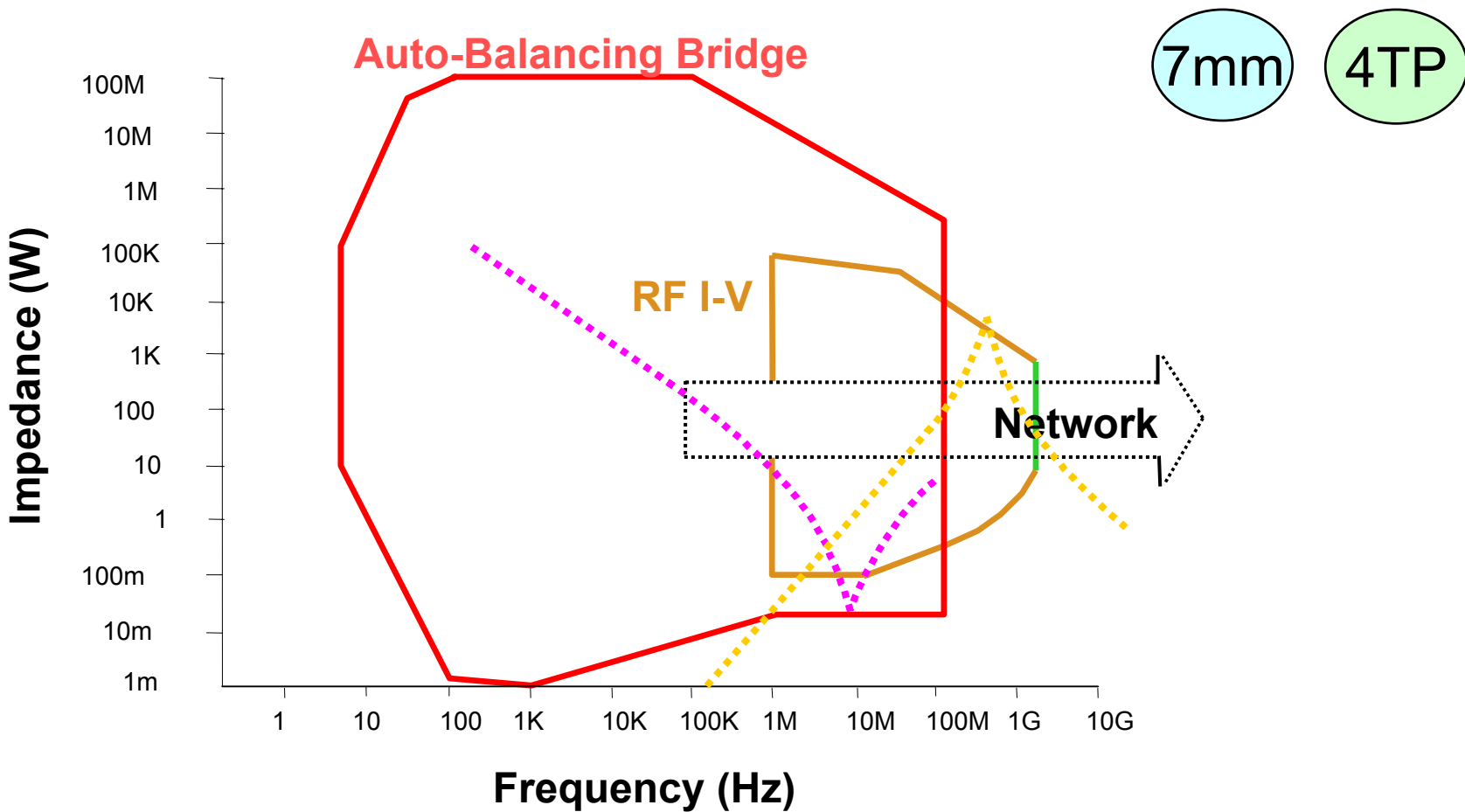
- 高阻抗测试



- 低阻抗测试



RF I-V 更宽的频率 & 阻抗测量范围



RF I-V法阻抗测量产品



Agilent Technologies E4491A
(1MHz – 3GHz)

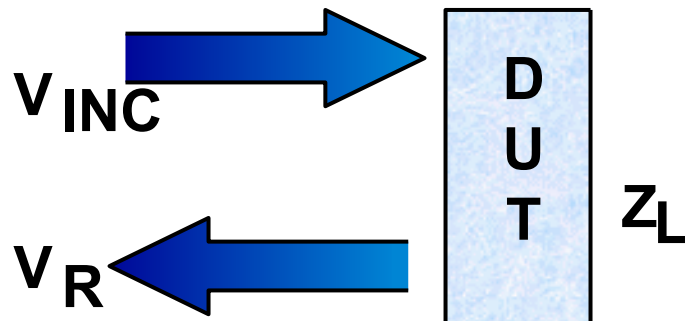


Agilent Technologies 4287A
(1MHz – 3GHz)



Agilent Technologies 4291B
(1MHz – 1.8GHz)

反射系数法 (网络分析仪)



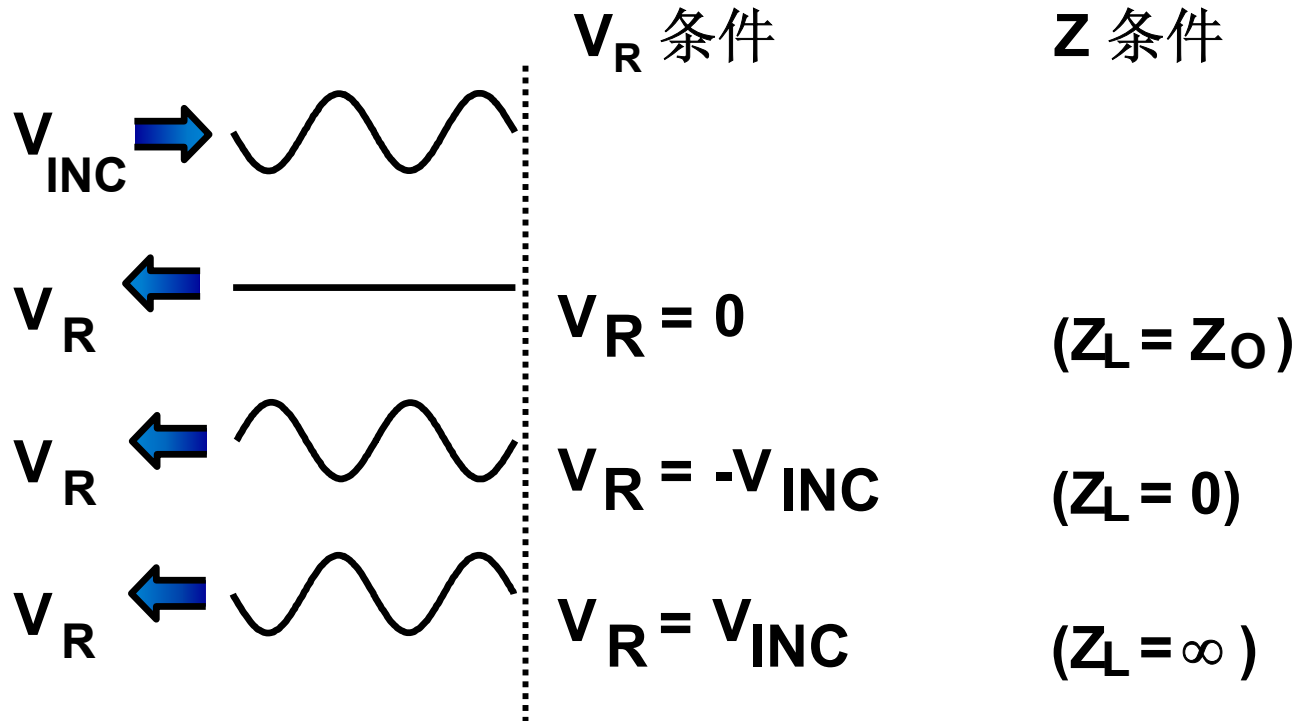
$$\Gamma = \frac{V_R}{V_{INC}} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Z_0 : 特性阻抗
 Γ : 反射系数

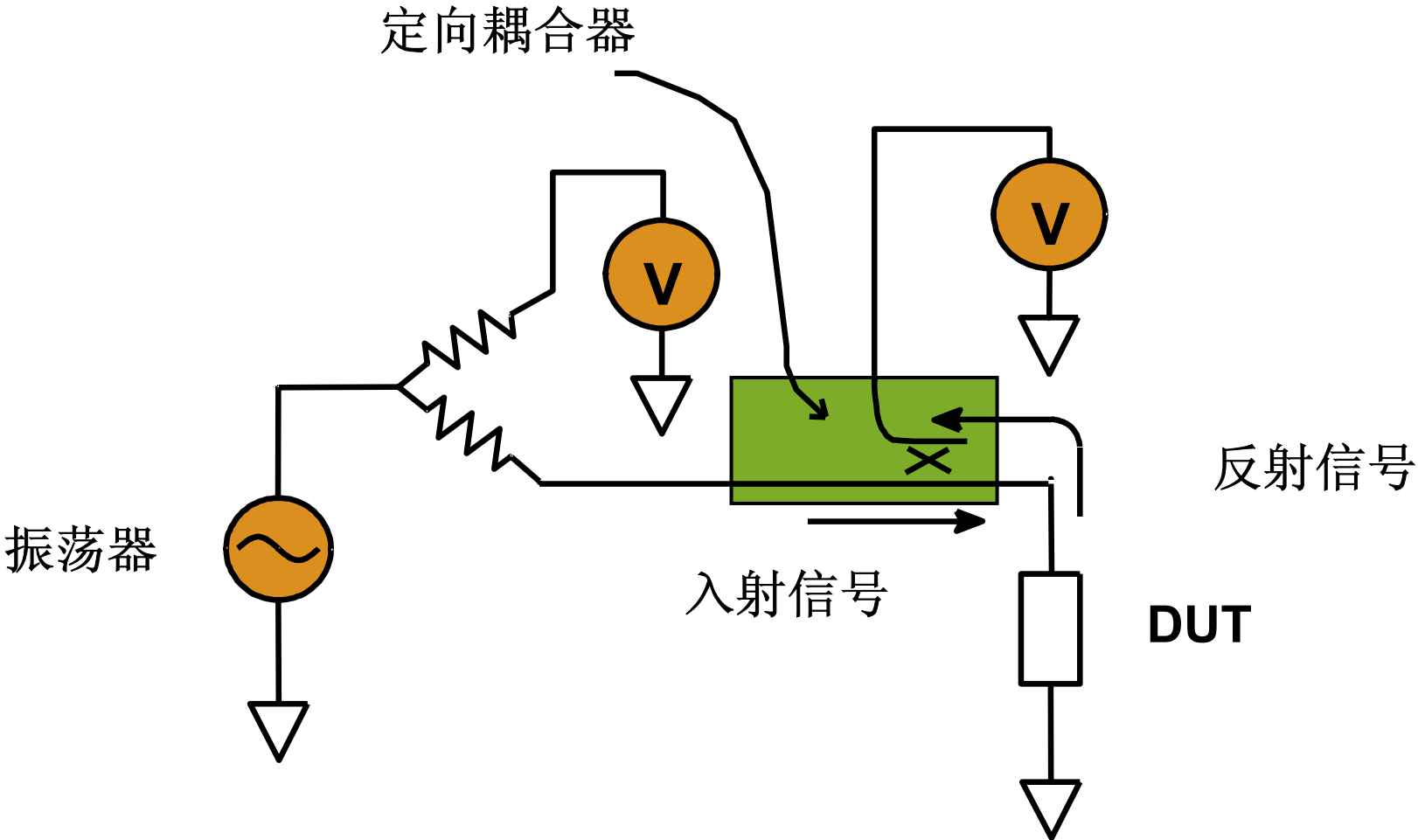


在不同边界条件下的反射波

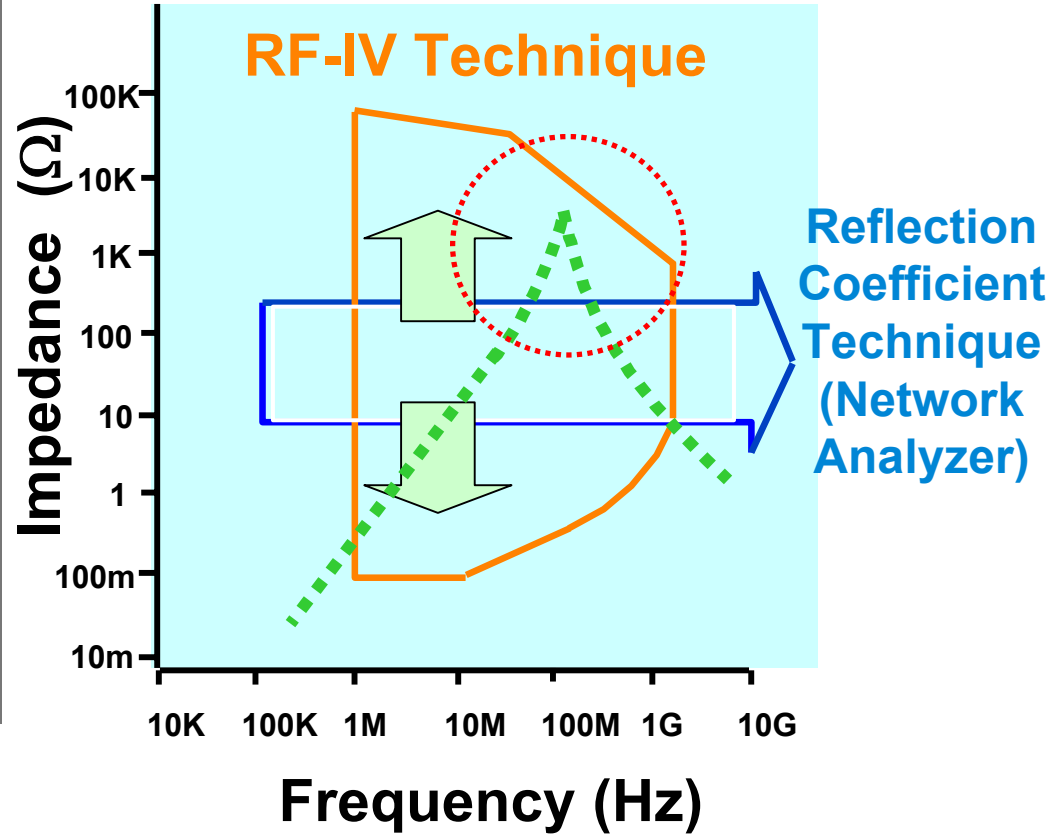
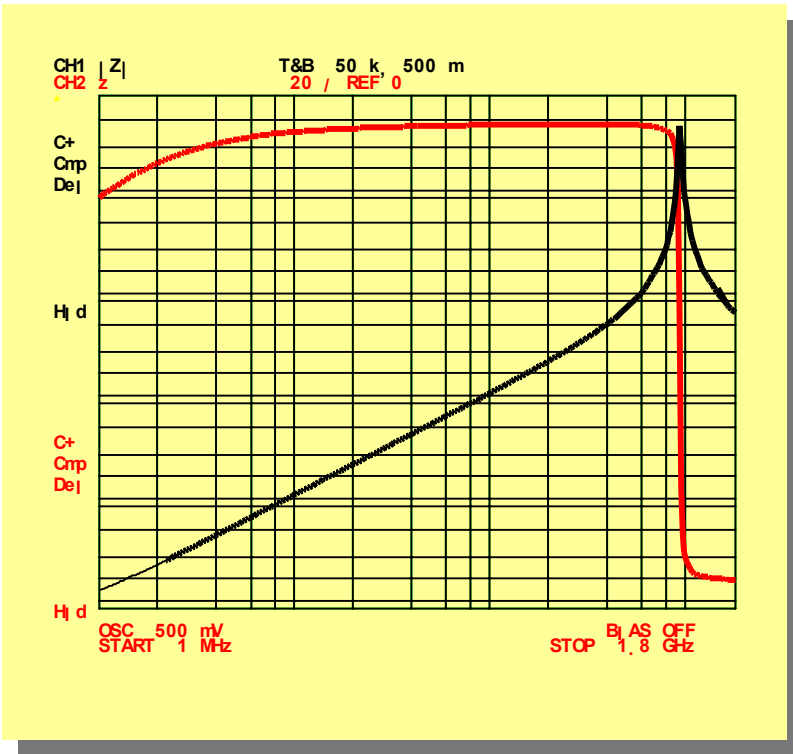
- **Waveform Examples**



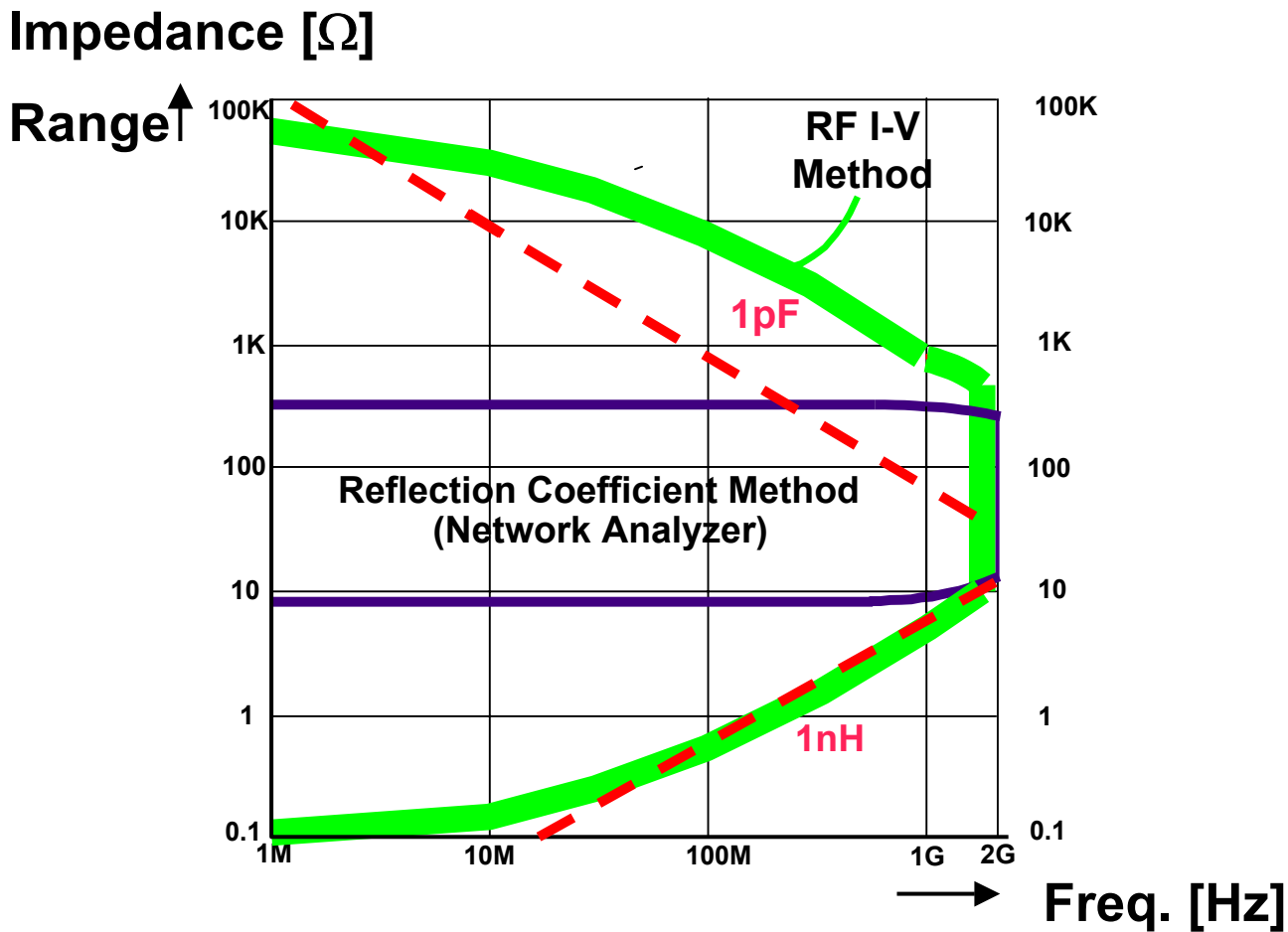
反射系数测量



射频I-V法 vs. 反射系数法

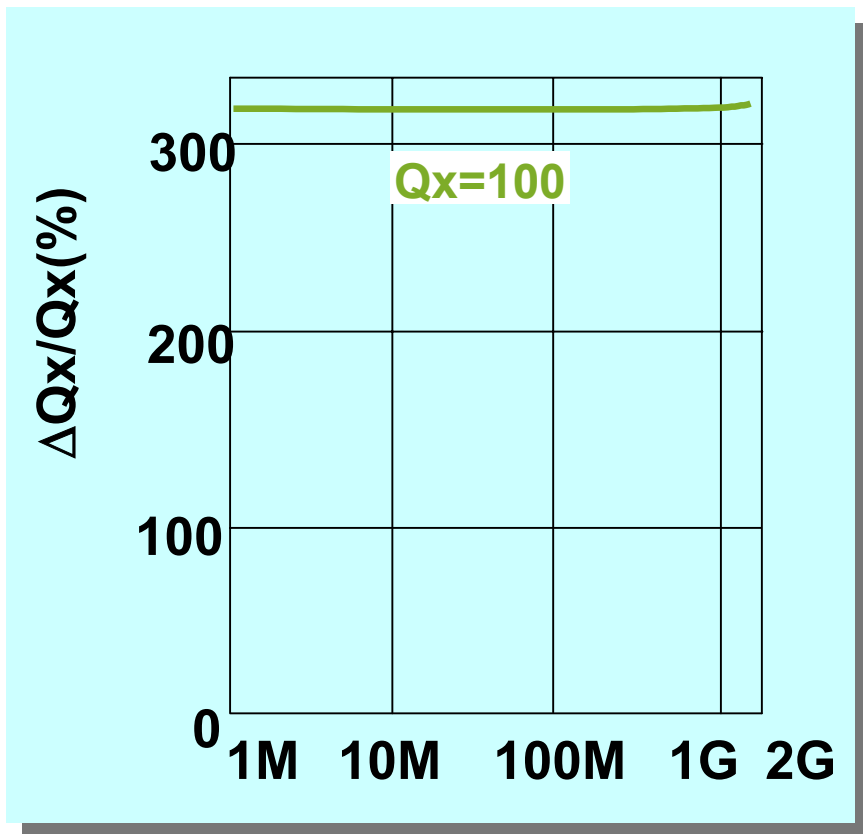


射频I-V法 vs. 反射系数法

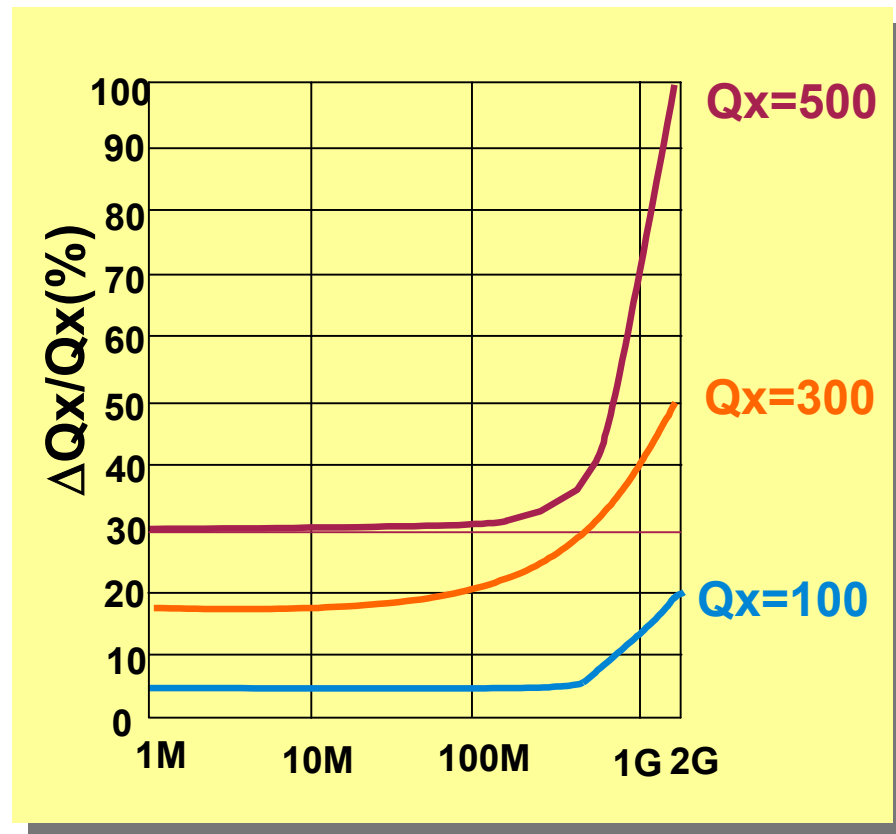


Q 因子测量精度

- 网络分析仪

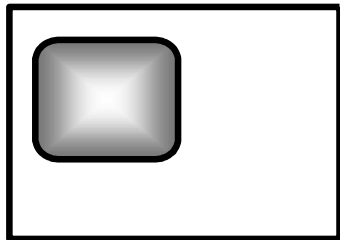


- 阻抗分析仪RF-IV

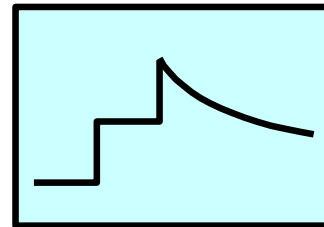
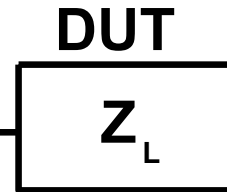
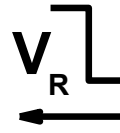
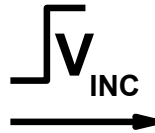
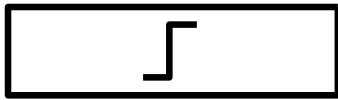


TDR (时域反射法)

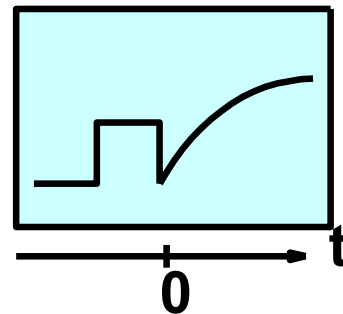
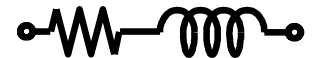
Oscilloscope



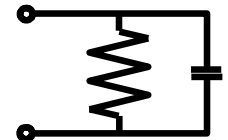
Step Generator



Series R and L



Parallel R and C



$$\Gamma = \frac{V_R}{V_{INC}} = \frac{Z_{OUT} - Z_0}{Z_{OUT} + Z_0}$$

Zo: Characteristic Impedance



网络分析仪和TDR产品



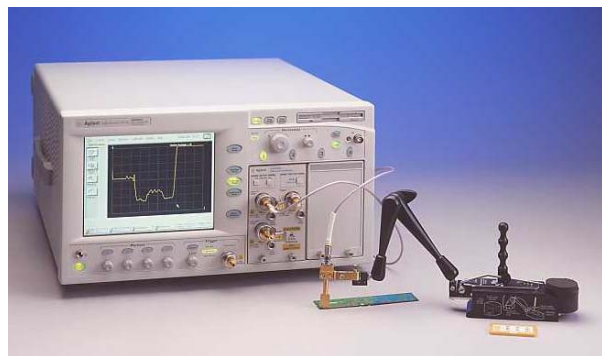
**Agilent 8752x and 8753x
(300KHz - 6GHz)**



**Agilent 8510x
(45MHz – 110GHz)**



**Agilent 8719x and 8720x
(130MHz – 20GHz)**

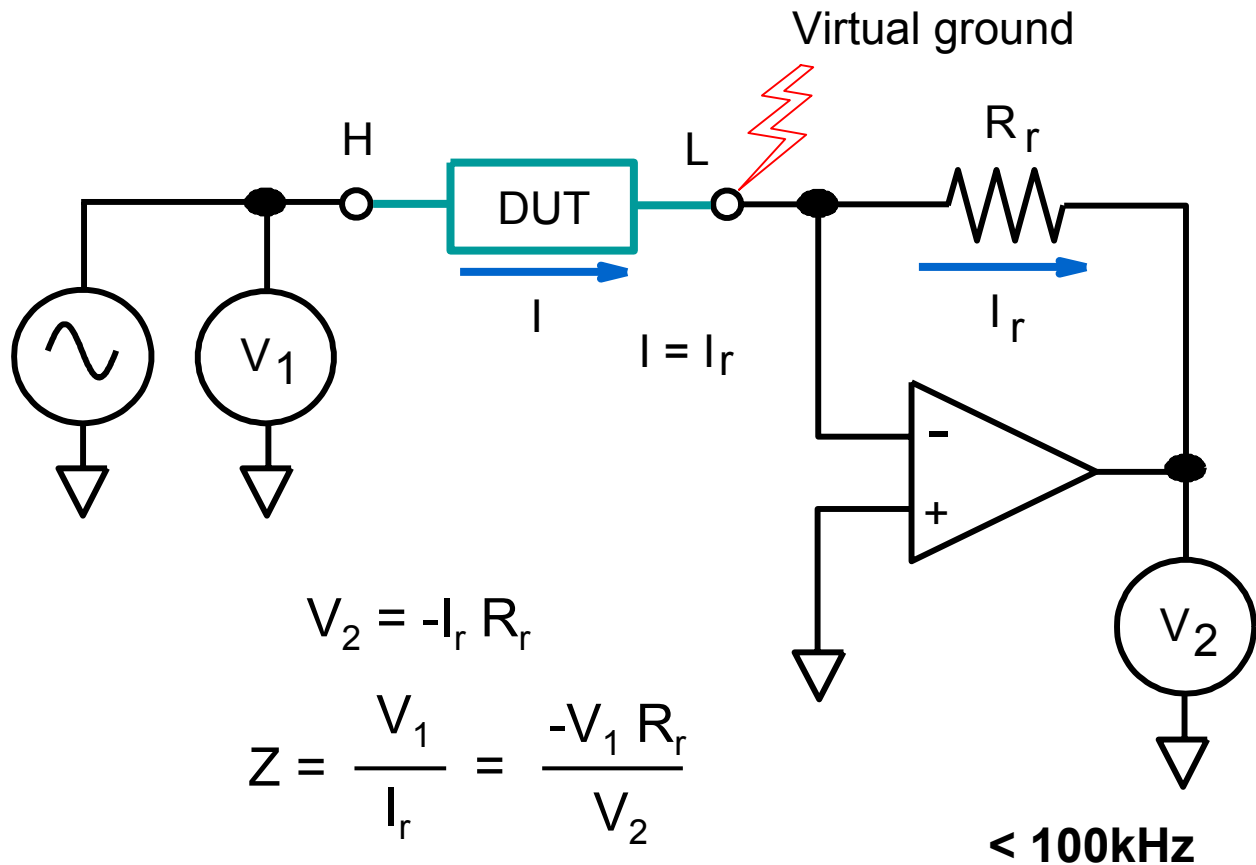


**Agilent 86100B DCA +
Agilent 54754A Differential TDR Module**



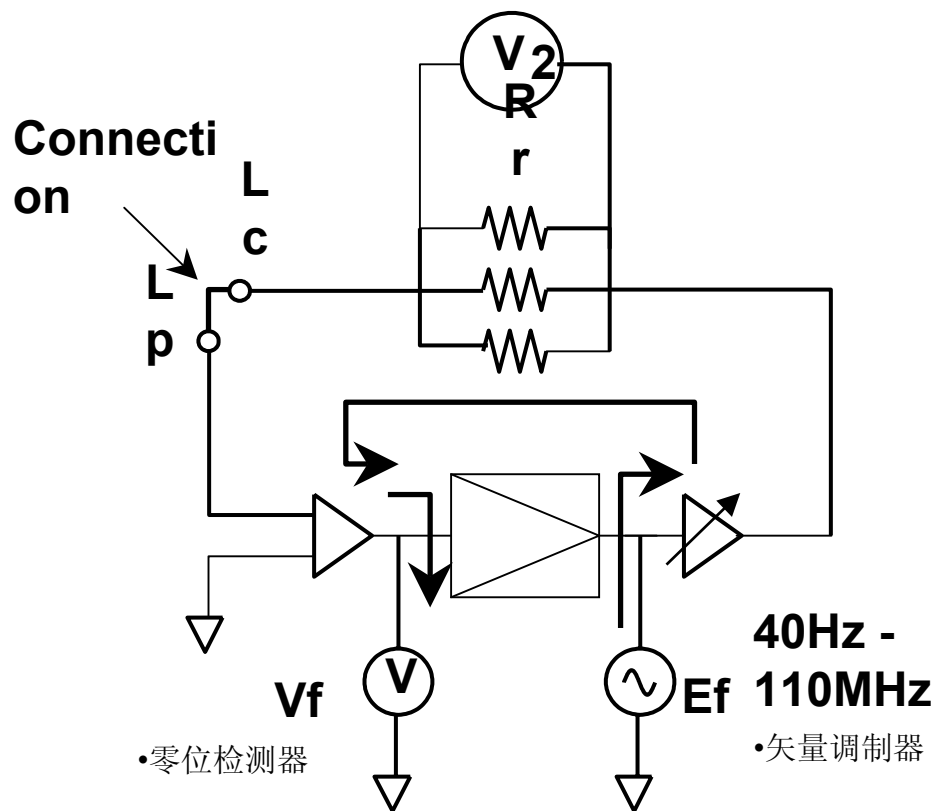
Agilent Technologies

自动平衡电桥法



自动平衡电桥法

- 高频平衡电桥电路
- 零回路相位特性补偿

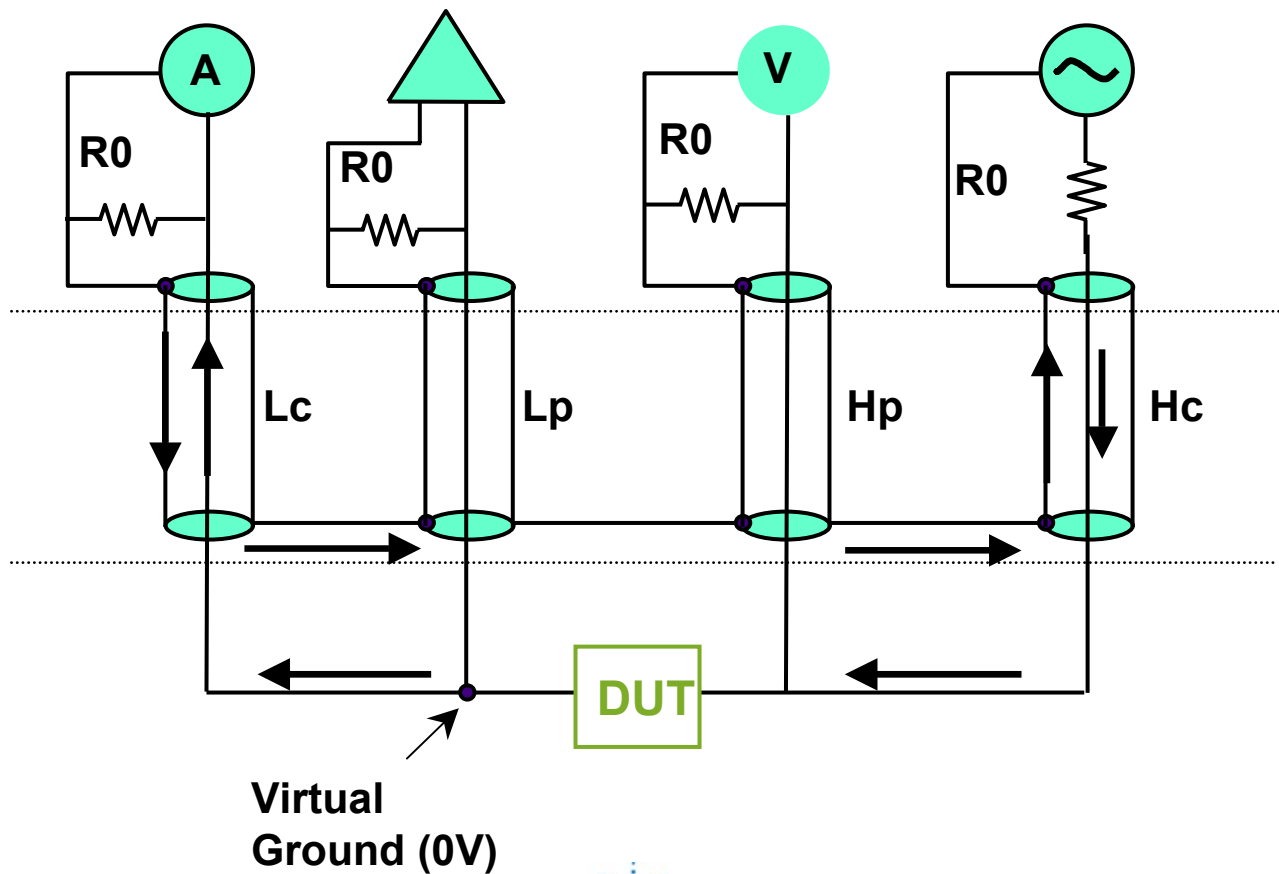


4TP

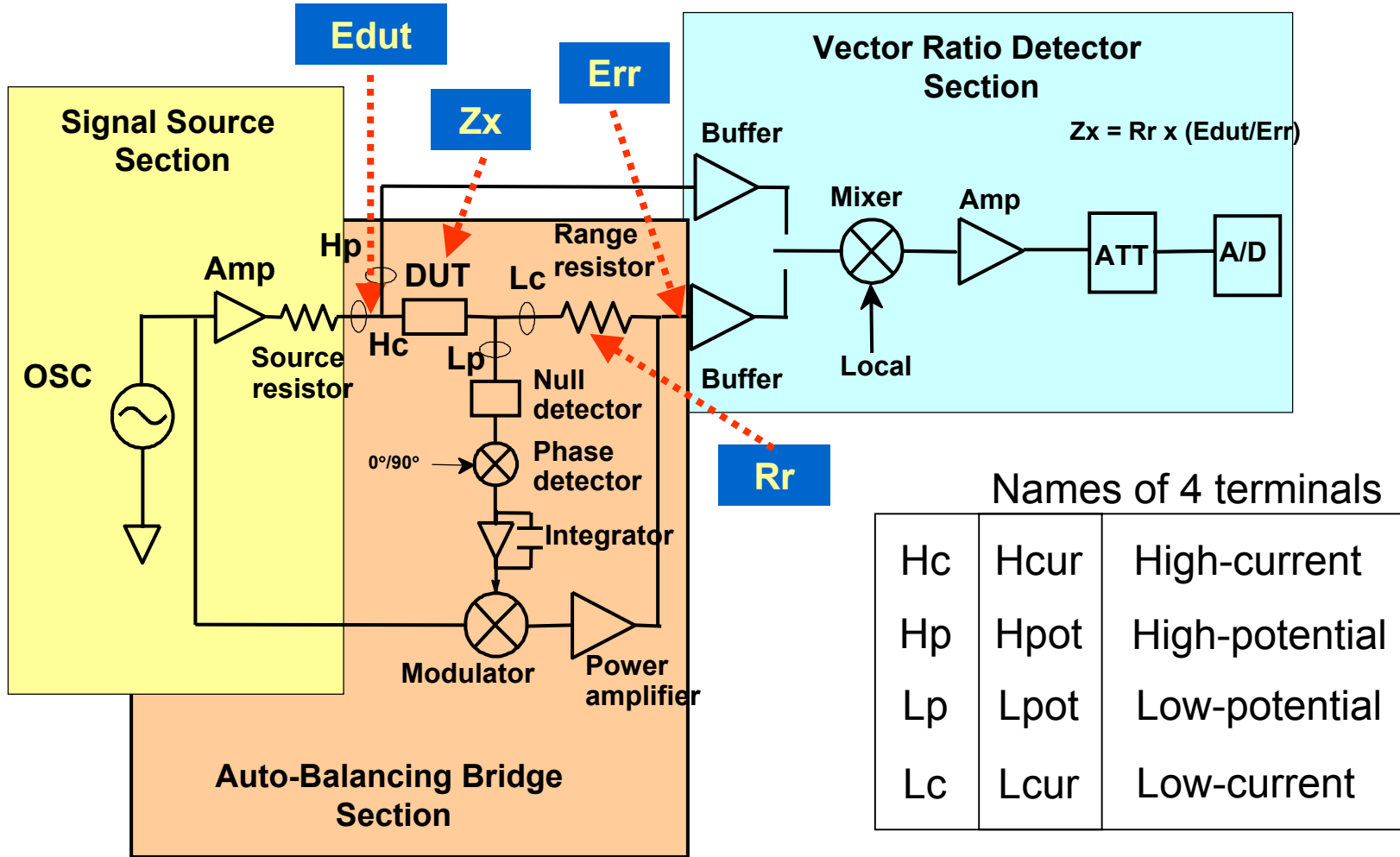
自动平衡电桥法

- 特性阻抗终端

4TP



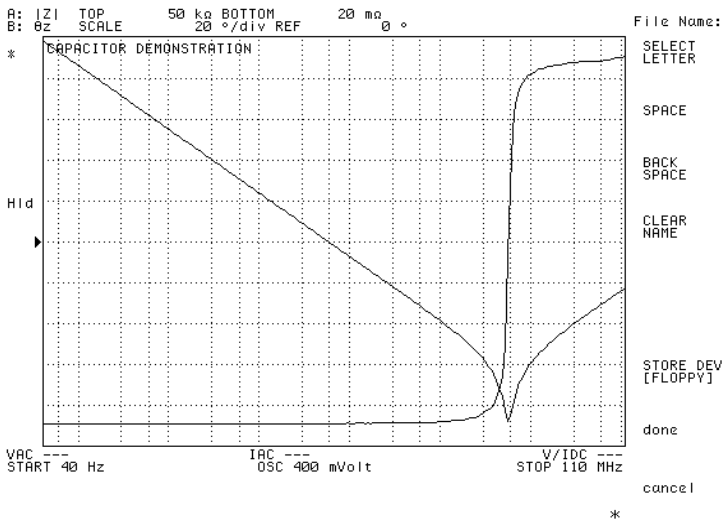
自动平衡电桥



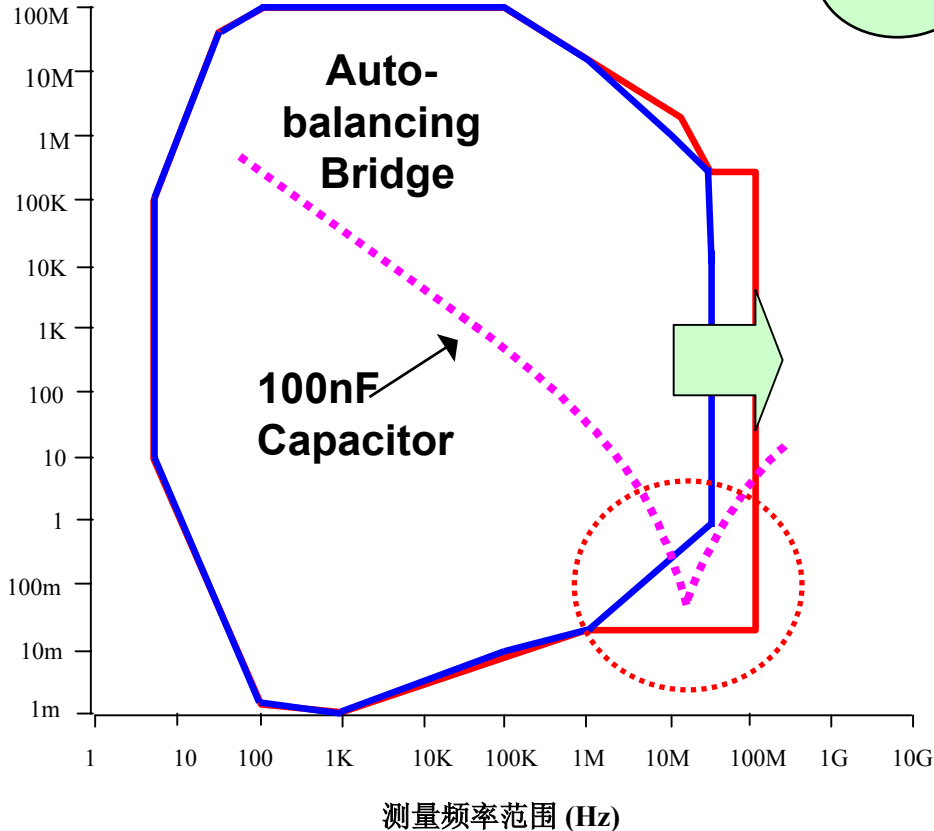
自动平衡电桥

- 频率/阻抗扩展
- 高频范围从**40MHz**扩展到**110MHz**

4TP



阻抗测量范围 (Ω)



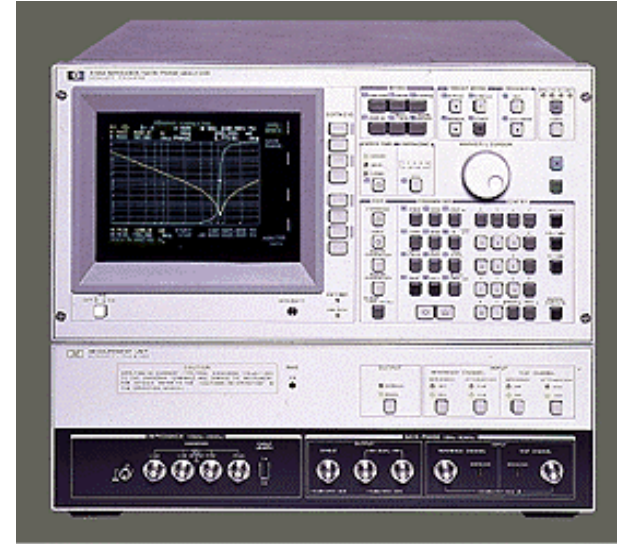
自动平衡电桥阻抗测试产品



**Agilent
4294A**



**Agilent 4263B, 4268A and
4288A**



**Agilent
4194A**



Agilent 4278A, 4279A, 4284A and 4285A



**Agilent
4192A**

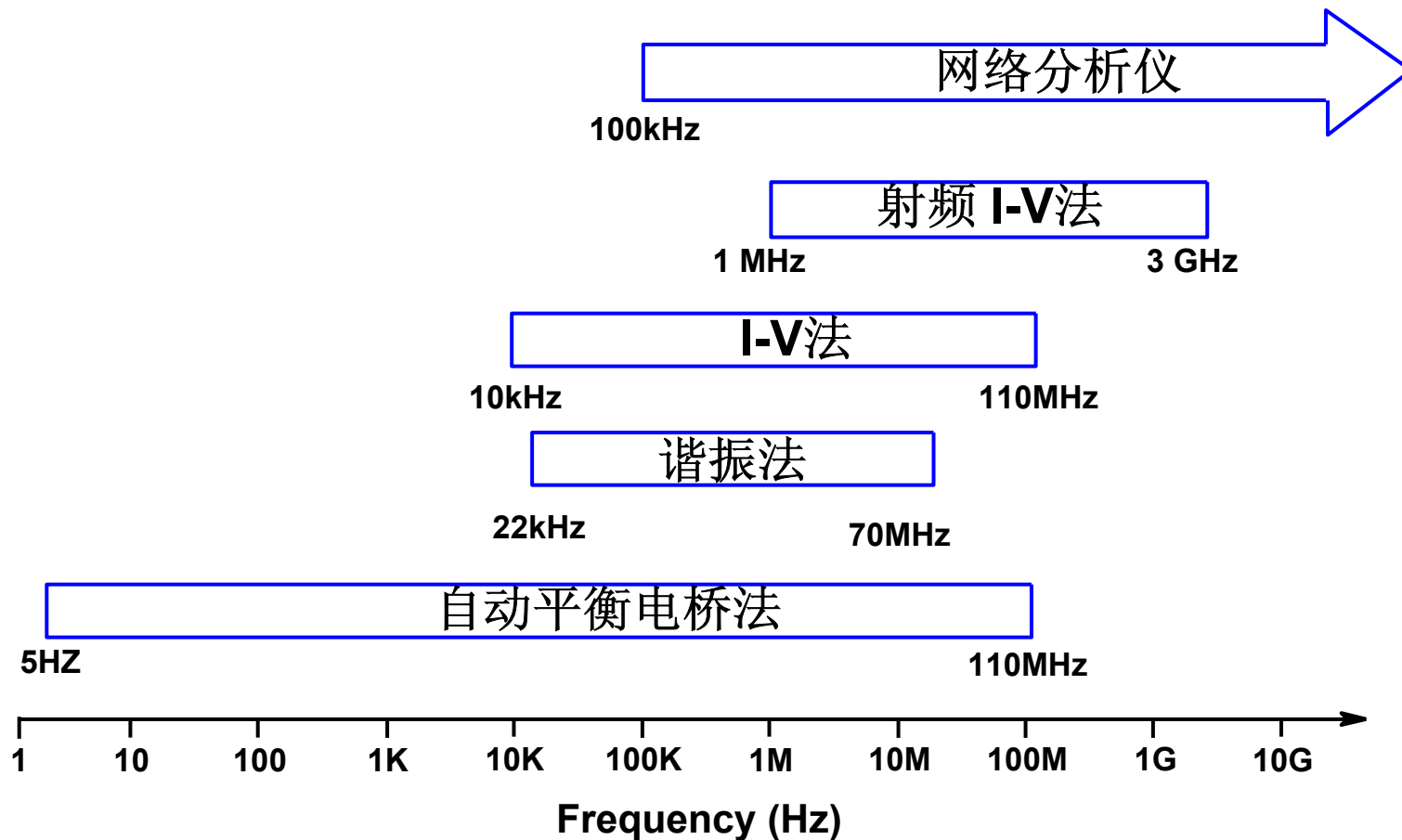


阻抗测量方法

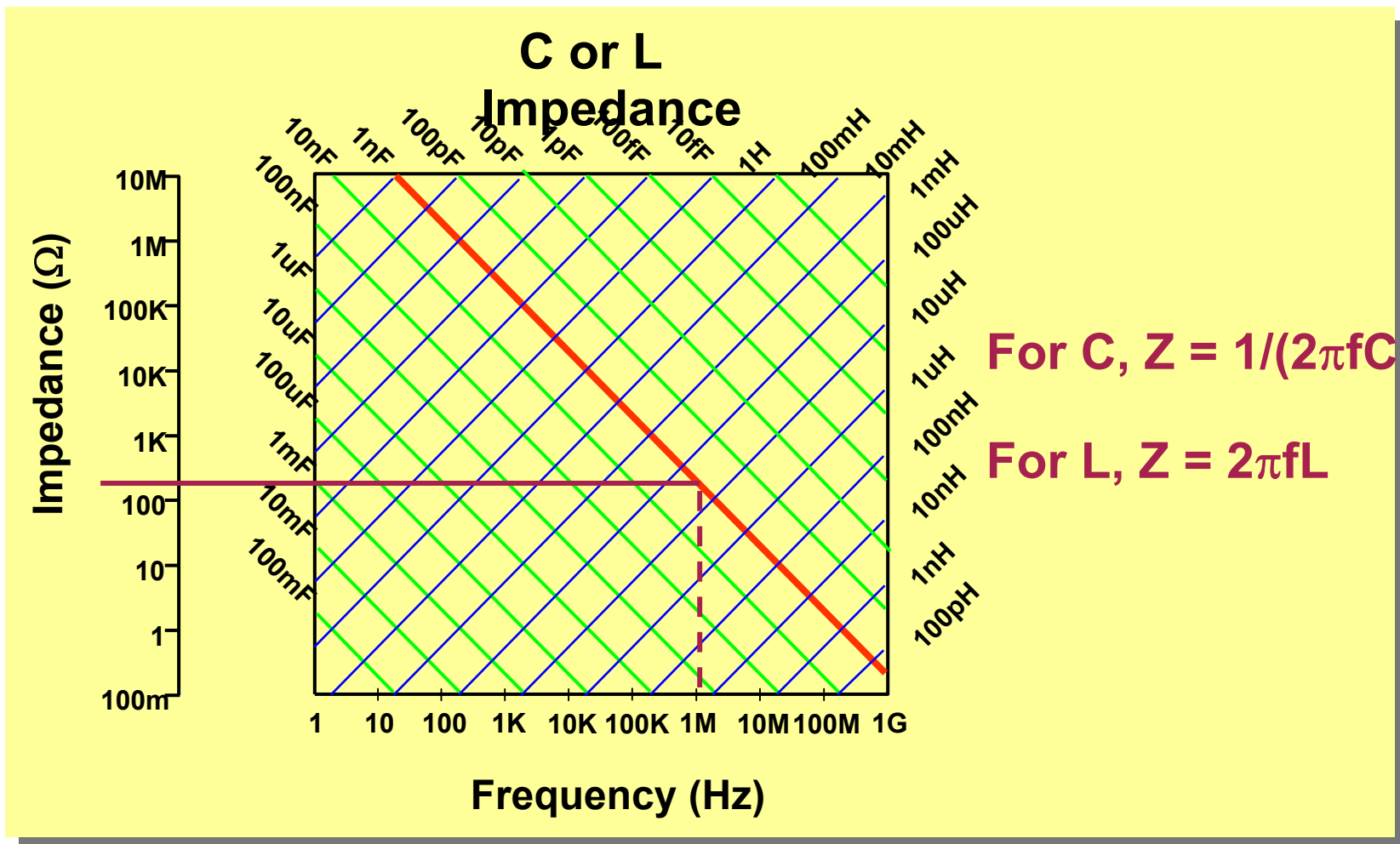
- 测量方法选择标准
 - 频率
 - **DUT** 阻抗
 - 要求测量精度
 - 测量条件
 - 测试参数
 - DUT的物理特性（尺寸，形状）



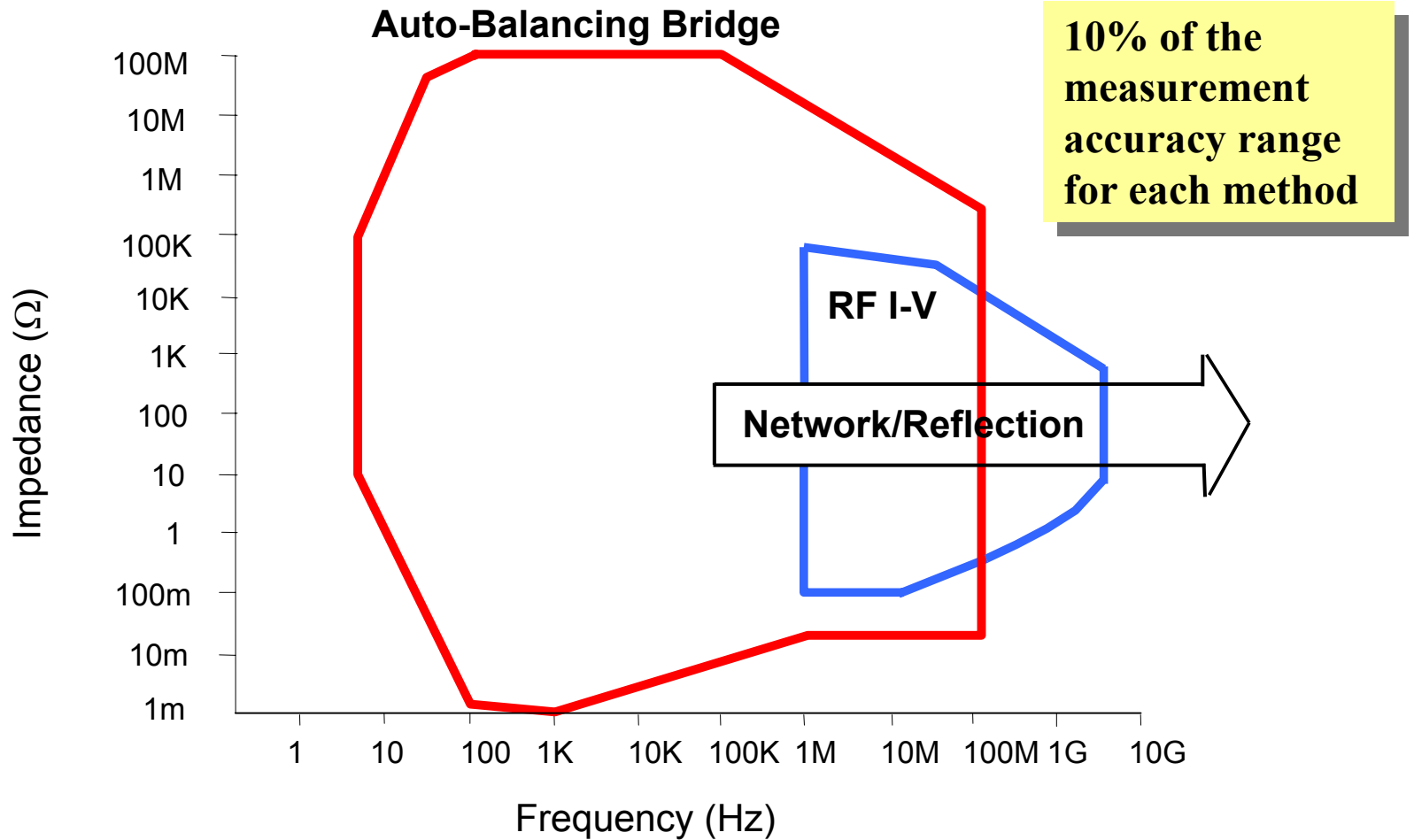
频率 vs 测量技术



阻抗图



阻抗测量方法



那种方法最好？

- **All are good.**
- **Each has advantages and disadvantages.**
- **Multiple techniques may be required.**

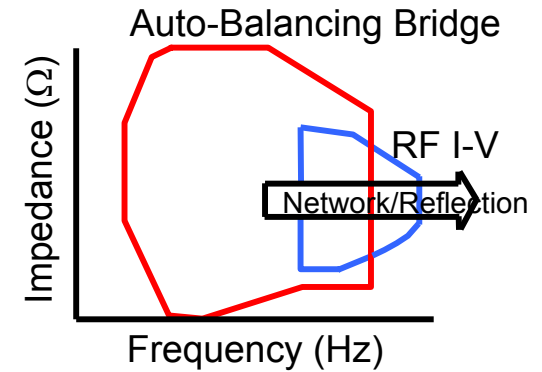


测量方法总结

| 测试方法 | 优点 | 缺点 | 频率范围 |
|---------|-----------------------------|---------------------------|-----------------|
| 电桥法 | 很宽频率范围高精度 (0.1%) | 需要手动平衡。对于单台仪器，只有较窄的频率覆盖范围 | DC - 300MHz |
| 谐振法 | 高Q值测量精度高。 | 需要调谐到谐振。阻抗测量精度低 | 10kHz - 70MHz |
| I-V | 可测量接地器件。适合于探头类测试需要。 | 工作频率范围受限于探头使用的互感器。 | 40Hz - 110MHz |
| 射频 I-V | 高精度 (1%). 高频下的宽阻抗范围。 | 工作频率范围受限于测试头使用的互感器。 | 1MHz - 3GHz |
| 反射系数法 | 高频范围 被测试阻抗接近特性阻抗时的高精度 | 单边测量频率需要重新校准。 阻抗测量范围窄 | 30kHz and above |
| 自动平衡电桥法 | 从LF至HF的宽频率覆盖范围。在宽的阻抗范围上的高精度 | 不能使用于更高频率范围。 | 5Hz - 110MHz |

测量方法选择

- 自动平衡电桥
 - 高精度, 高 **Q** 和低 **D** 测量, 频率范围 **< 110MHz**
- **RF I-V**
 - 高频测量, 高 **Q** 和低 **D** 测量, 频率范围 **1MHz-3 GHz**
- 网络分析仪
 - 高频测量 **> 3 GHz**
- **TDR**
 - 分布特性和不连续性测试



测量方法和产品

| 测量方法 | 产品 | 频率范围 |
|---|---|----------------------|
| Auto-balancing Bridge (Four-Terminal Pair) | 4263A/B LCR Meters | 100Hz to 100KHz spot |
| | 427xA Capacitance Meters | 100Hz to 10MHz spot |
| | 4284A Precision LCR Meter | 20Hz to 1MHz spot |
| | 4285A Precision LCR Meter | 75KHz to 30MHz |
| | 4192A LF Impedance Analyzer | 5Hz to 13MHz |
| | 4194A/4294A Impedance/Gain-Phase | 10Hz to 40/110MHz |
| Resonant (Q-Meter) | 4342A Q-Meter | 22KHz to 70 MHz |
| | 42851A Q Adapter (used with 4285A) | 75KHz to 30 MHz |
| I-V | 4194A/4294A Impedance/Gain-Phase Analyzer with 41941A/42941A Impedance Probe | 10KHz to 100/110MHz |
| | 4193A Vector Impedance Meter | 400KHz to 110MHz |
| | E4916A Crystal Impedance/LCR Meter Opt. 010 | 1MHz to 180MHz |
| | | |
| RF I-V | 4286A RF LCR Meter | 1MHz to 1GHz |
| | 4287A RF LCR Meter | 1MHz to 3GHz |
| | 4291A/B RF Impedance/Material Analyzer | 1MHz to 1.8GHz |
| | E4991A RF Impedance/Material Analyzer | 1MHz to 3GHz |



测量方法和产品

| 测量方法 | 产品 | 频率范围 |
|-------------------------|---|------------------------------------|
| Network Analysis | 4191A RF Impedance Analyzer | 1MHz to 1GHz |
| | 4195A Network/Spectrum Analyzer with 41951A Impedance Test Set | 10Hz to 500MHz 10KHz to 500MHz |
| | 4395A & 4396A/B Network/Spectrum Analyzer with 43961A Impedance Test Set | 100KHz to 1.8 GHz |
| | 8751A Network Analyzer | 5Hz to 500MHz |
| | 875x RF Network Analyzers | 300KHz to 1.3/3/6GHz |
| | 8510x Network Analyzer | 45 MHz to 100GHz |
| | 8719x and 872x Network Analyzers | 130MHz to 13.5GHz/20GHz |
| | 871x Network Analyzer E5100A/B Network Analyzer | 100KHz to 3 GHz 10KHz to 300MHz |
| TDNA (TDR) | 54121T Digitizing Oscilloscope and TDR | 300KHz to 1.3GHz/6GHz |
| | 8752A/C/8753C/D RF Network Analyzers | 300KHz to 1.3GHz/6GHz |
| | 8510B Network Analyzer | 45 MHz to 100GHz |
| | 8719A/C/8720B/C Network Analyzers | 130MHz to 13.5GHz/20GHz |



428X系列LCR表

- 4284A 精密LCR表 (20 Hz to 1 MHz; 10m~100M Ω)
- 4285A 通用精密LCR表 (75 kHz to 30 MHz; 10m~100M Ω)
- 4287A RF LCR表 (1 MHz to 3 GHz; 200m~3k Ω)
- 4288A 电容表 (1 kHz/1 MHz; 1m~100M Ω)



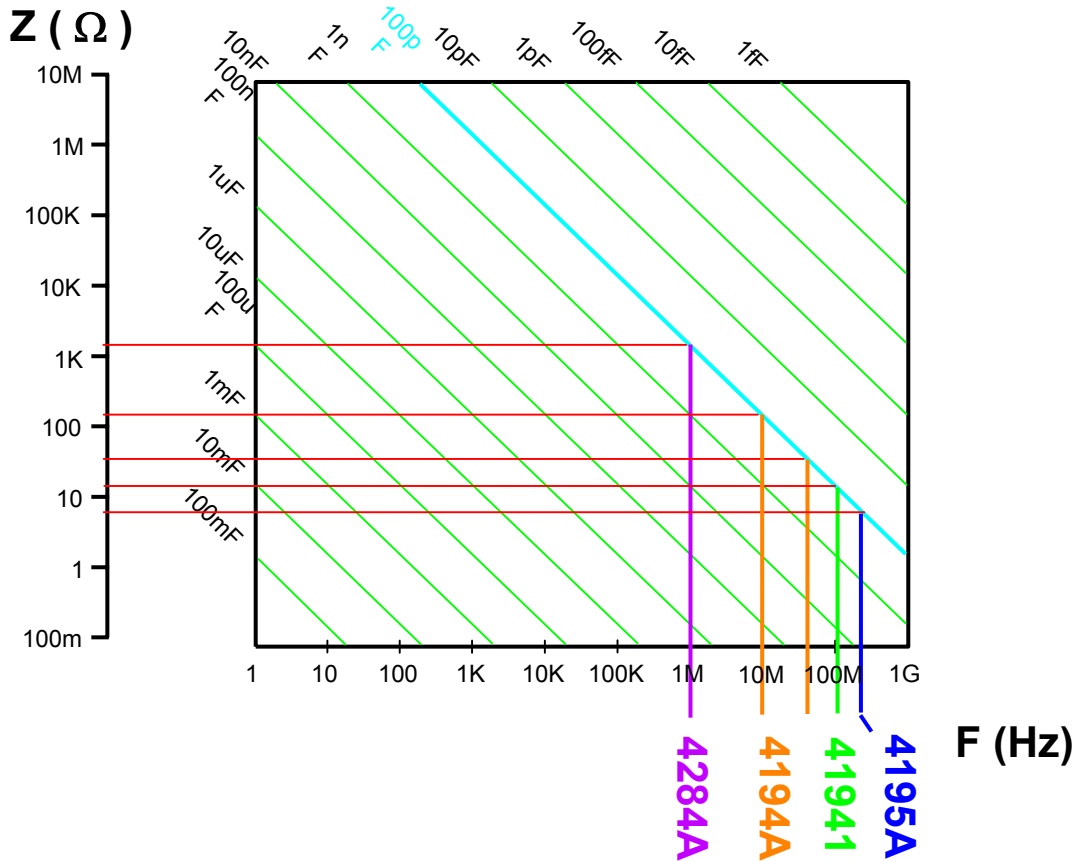
选择一个测试频率

- 理想情况——工作条件.
- 实际上——必须折衷处理.
- 越高的测试频率, 测试夹具和仪表误差越大.
- 毫欧(m ohms)和兆欧(M ohms) - **DUTs** 测量困难.



测量折衷举例

- 希望测量 **100 pF 理想电容 @ 200 MHz:**



精度比较

4284A @ 1MHz (1600 Ω) : 0.05%

4194A @ 10MHz (160 Ω) : 1.3 %

4194A @ 40MHz (40 Ω) : 5.2 %

41941A @ 40MHz (40 Ω) : 3.6 %

41941A @ 100MHz (16 Ω) : 6.2 %

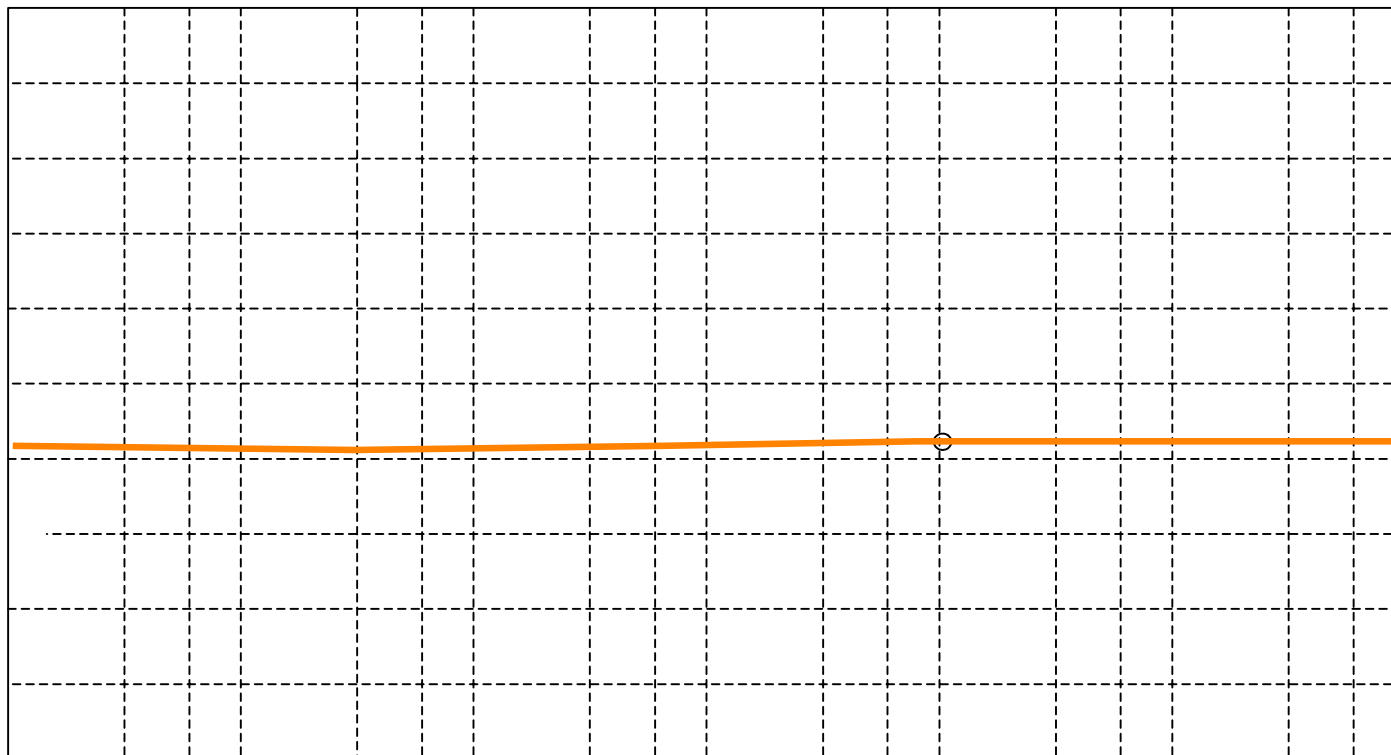
4195A @ 200MHz (8 Ω) : 1.9 %



自动平衡电桥

A: Cp B: D
A MAX 13.00 pF
B MAX 350.0 m

○ MKR 1 006 570.375 Hz
Cp 10.0742 pF
D



A/DIV 500.0 fF
B/DIV 50.00 m

START 1 000.000 Hz
STOP 40 000 000.000 Hz

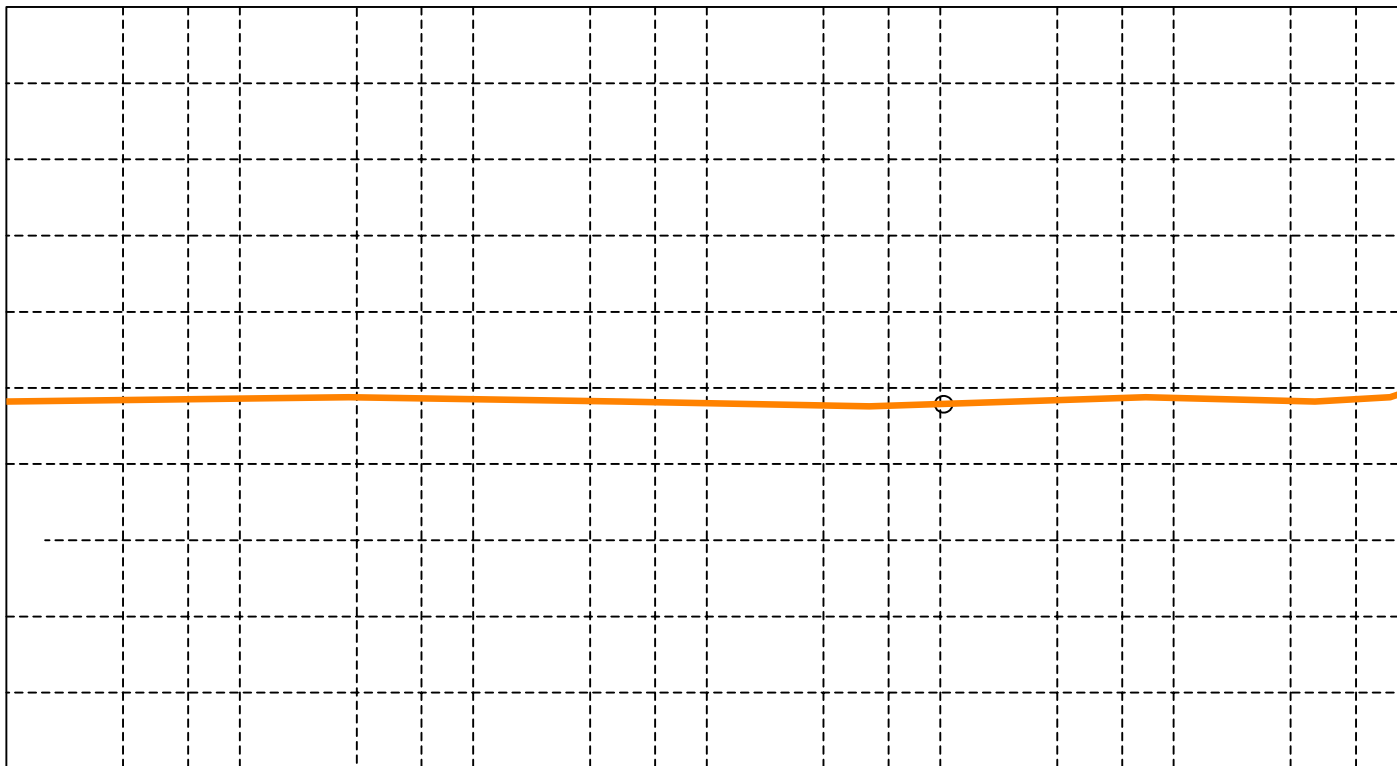


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I-V

A: Cp
A MAX 13.00 pF
B MAX 1.000

○ MKR 1 011 579.454 Hz
Cp 10.4523 pF
D



A/DIV 500.0 fF
B MIN 0.000

START 100 000.000 Hz
STOP 100 000 000.000 Hz



Agilent Technologies

网络分析仪

IMPEDANCE

A: REF

13.00p

[F]

B: REF

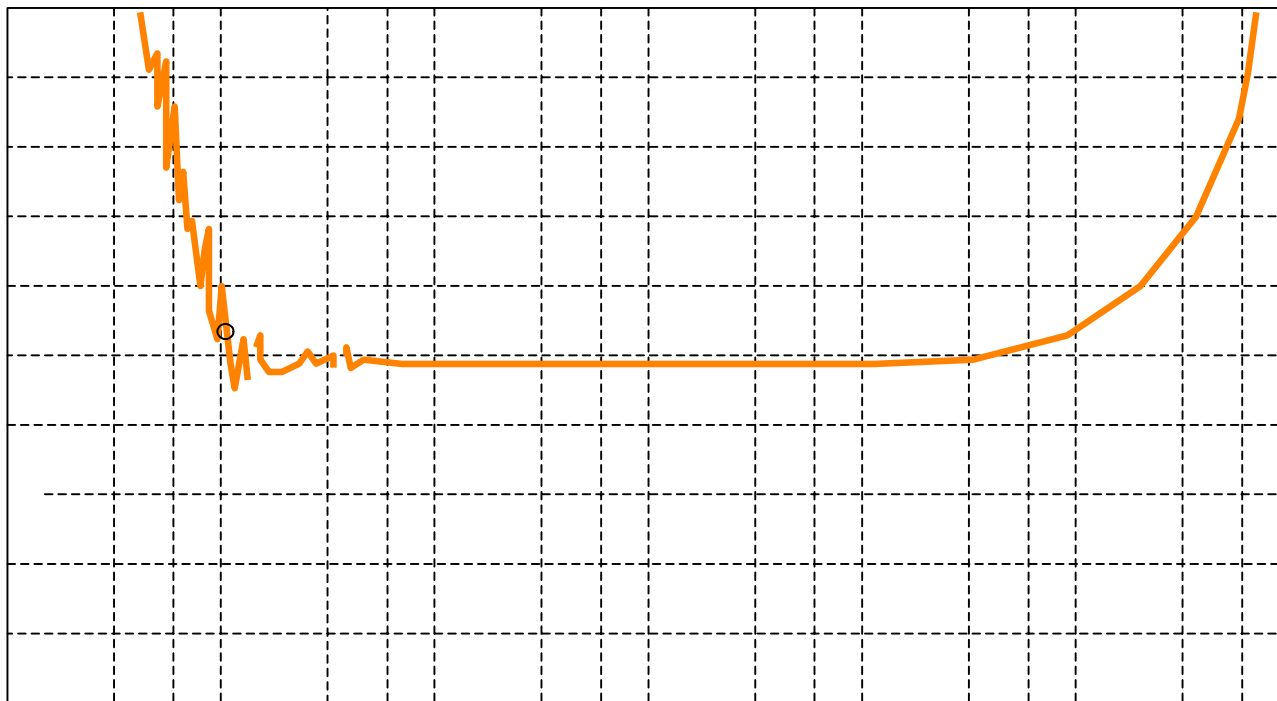
180.0

[F]

○ MKR 1 018 519.448 Hz

Cp 10.7531p F

D



DIV

500.0f

DIV

36.00

START 100 000.000 Hz

STOP 500 000 000.000 Hz

RBW: 3 KHZ ST: 6.15 sec RANGE: A = 0, T = 0dBm

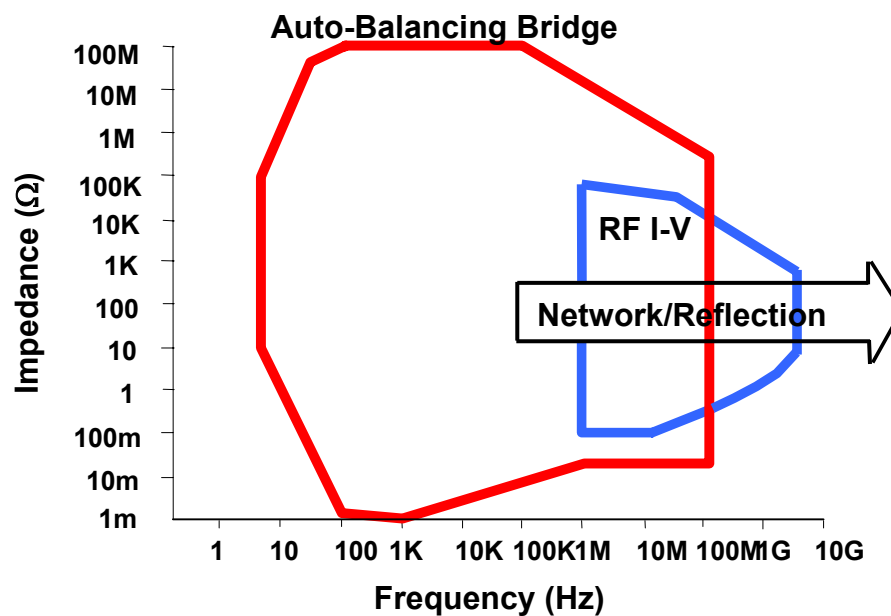


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内容安排

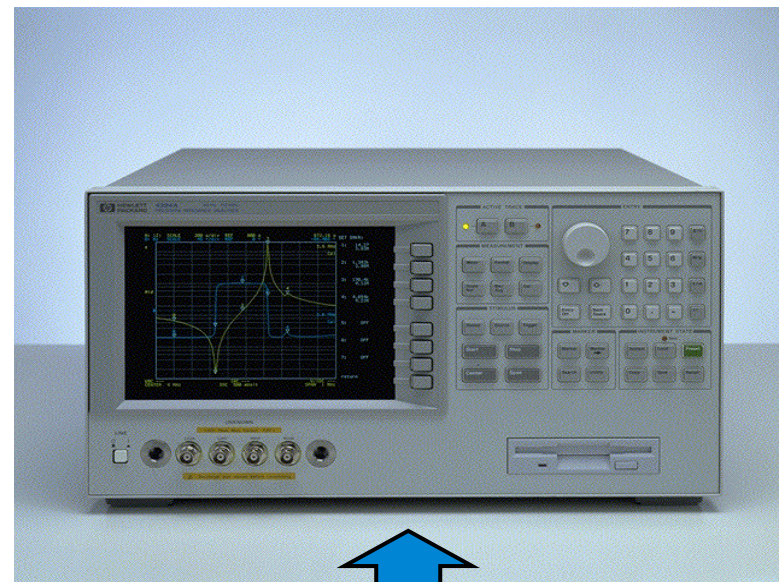
阻抗测量基础

- 阻抗基础
- 阻抗测量方法
- 夹具和电缆连接
- 校准和补偿
- 总结



连接方法和测试夹具

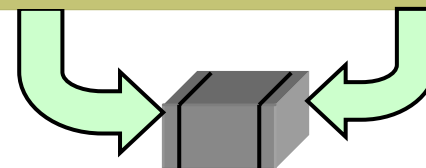
- 终端配置
- 电缆长度
- 夹具类型



电缆



夹具

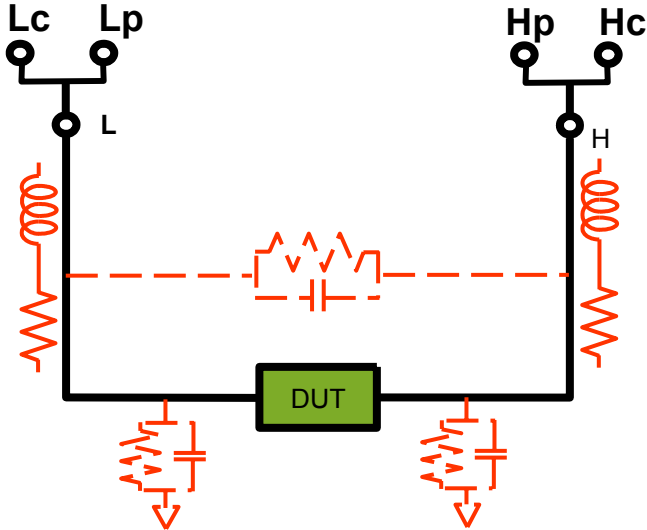


DUT

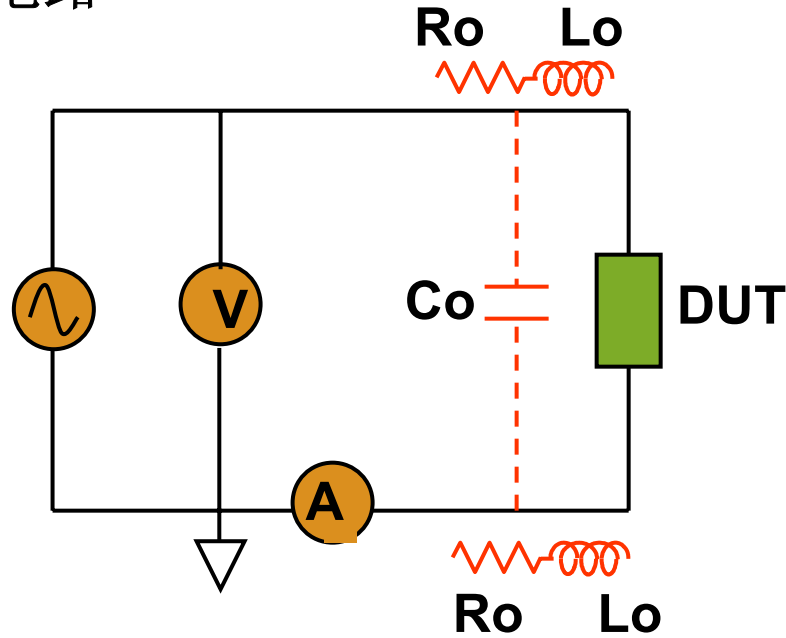


2端(2T)连接

A. 连接方法

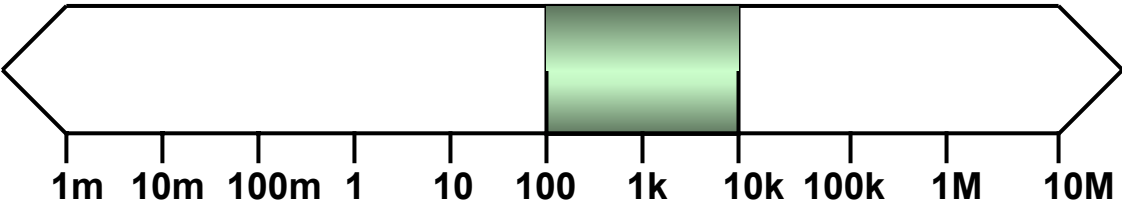


B. 电路



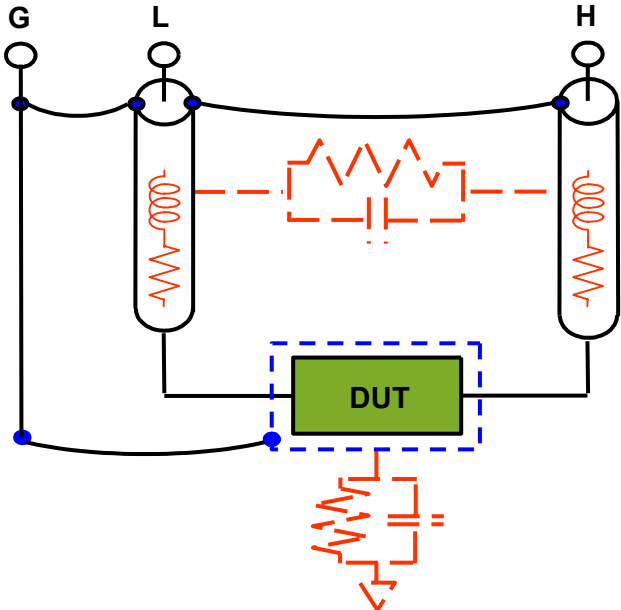
引线电感
引线电阻
寄生电容

C. 阻抗测量范围 (Ω)

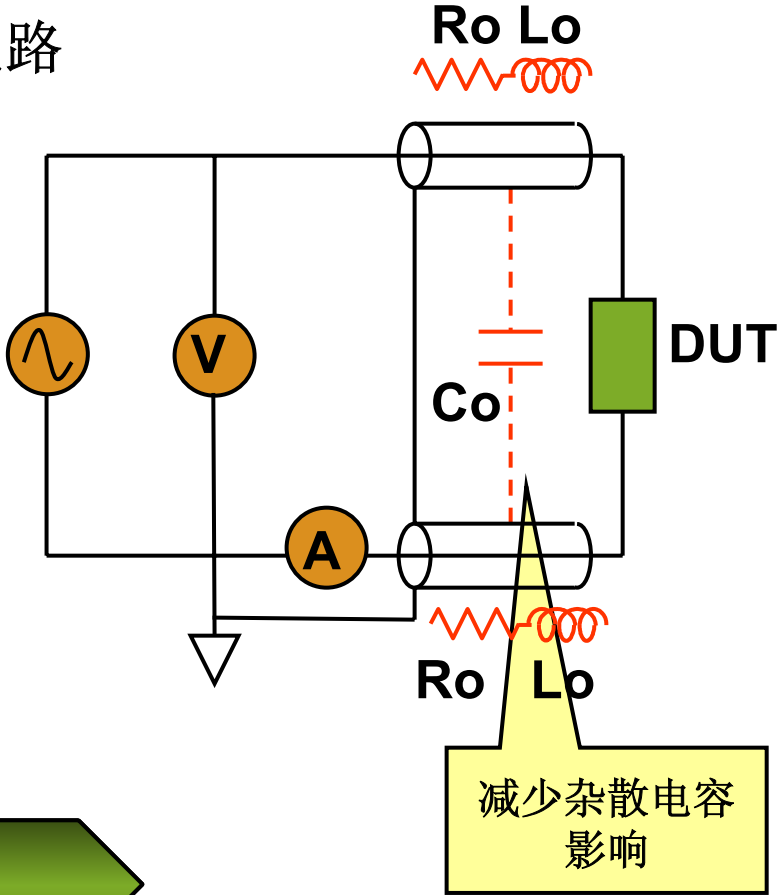


3端(3T)连接

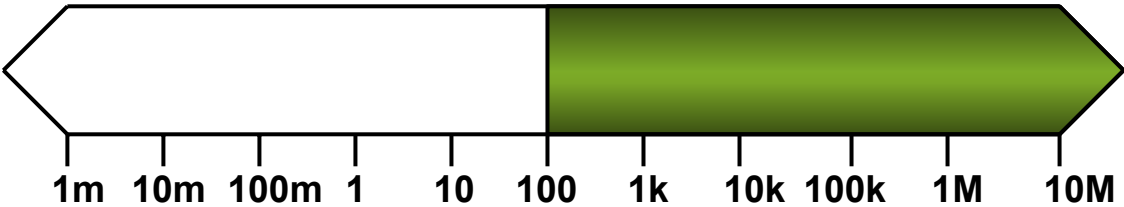
A. 连接



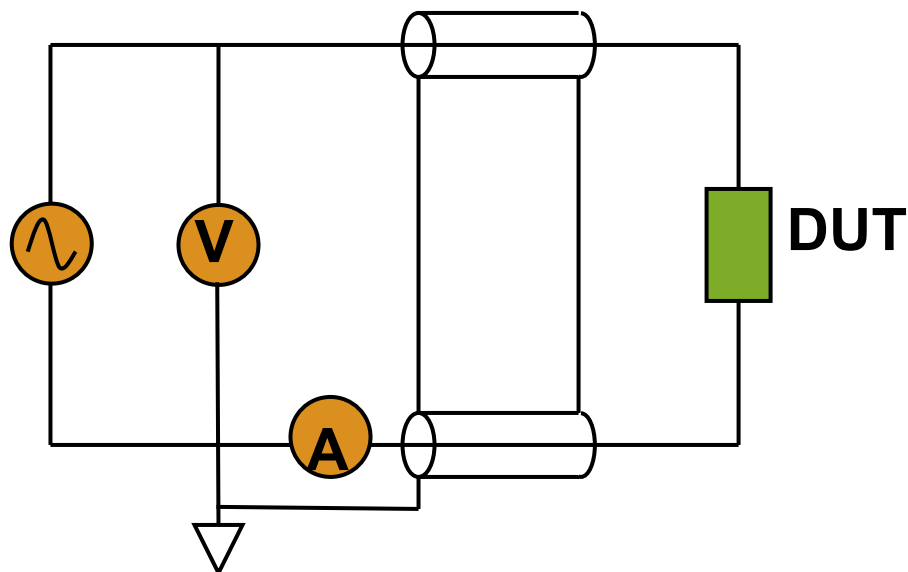
B. 电路



C. 阻抗测量范围 (Ω)



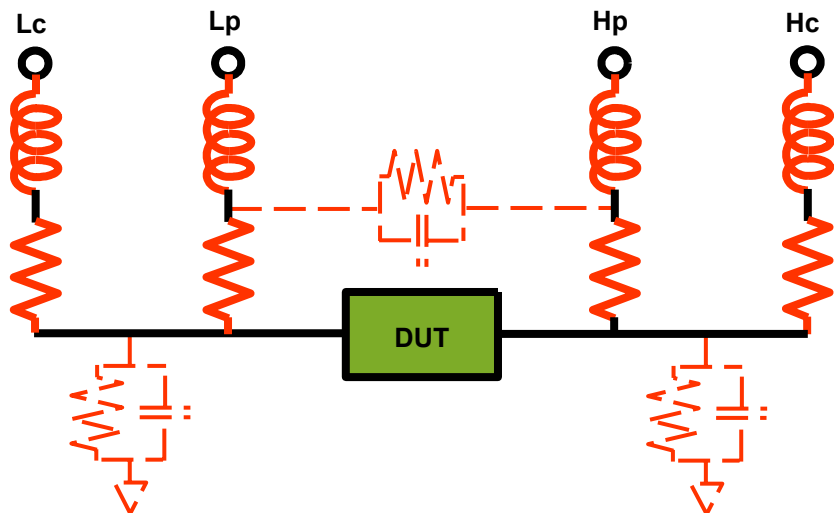
屏蔽2端(2T)连接



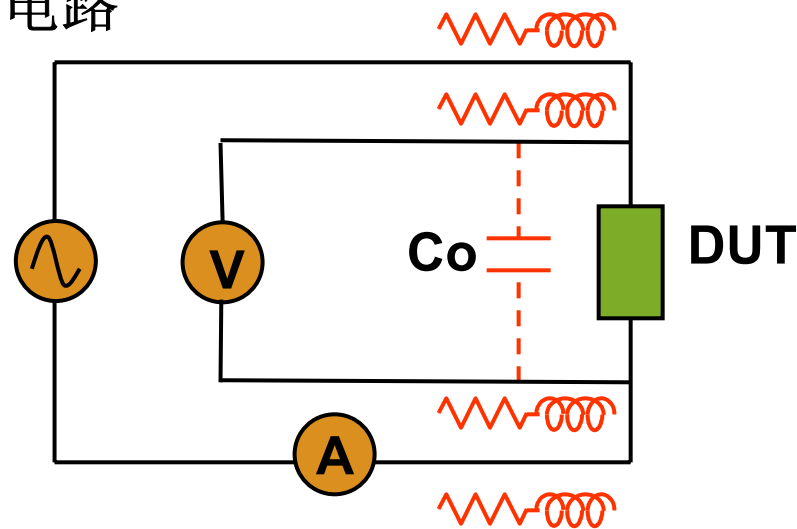
减少电缆残留电感，从而提高低阻抗测量性能

4端(4T)连接

A. 连接

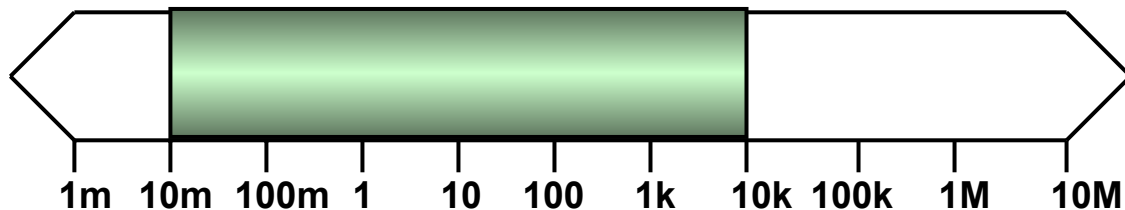


B. 电路



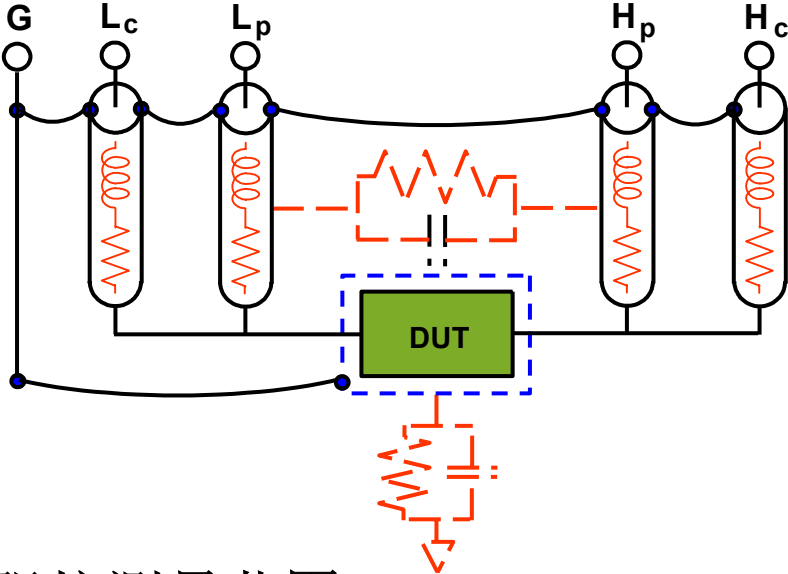
减小引线电感影响
信号电流通路和电压敏感电缆彼此独立

C. 测量阻抗范围 (Ω)

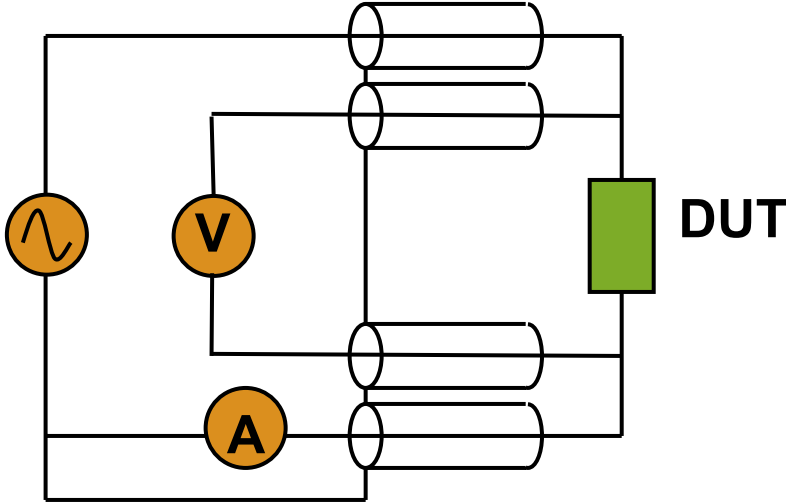


5端(5T)连接

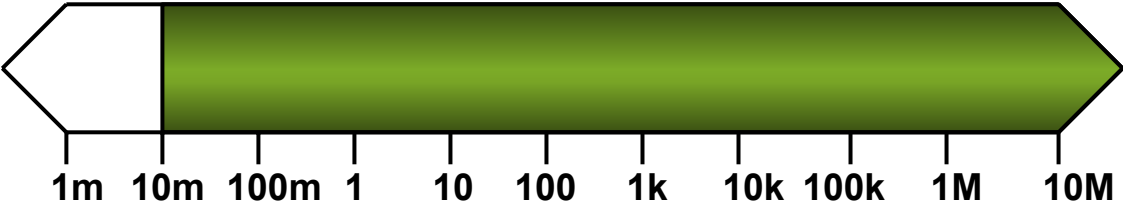
A. 连接方法



B. 电路

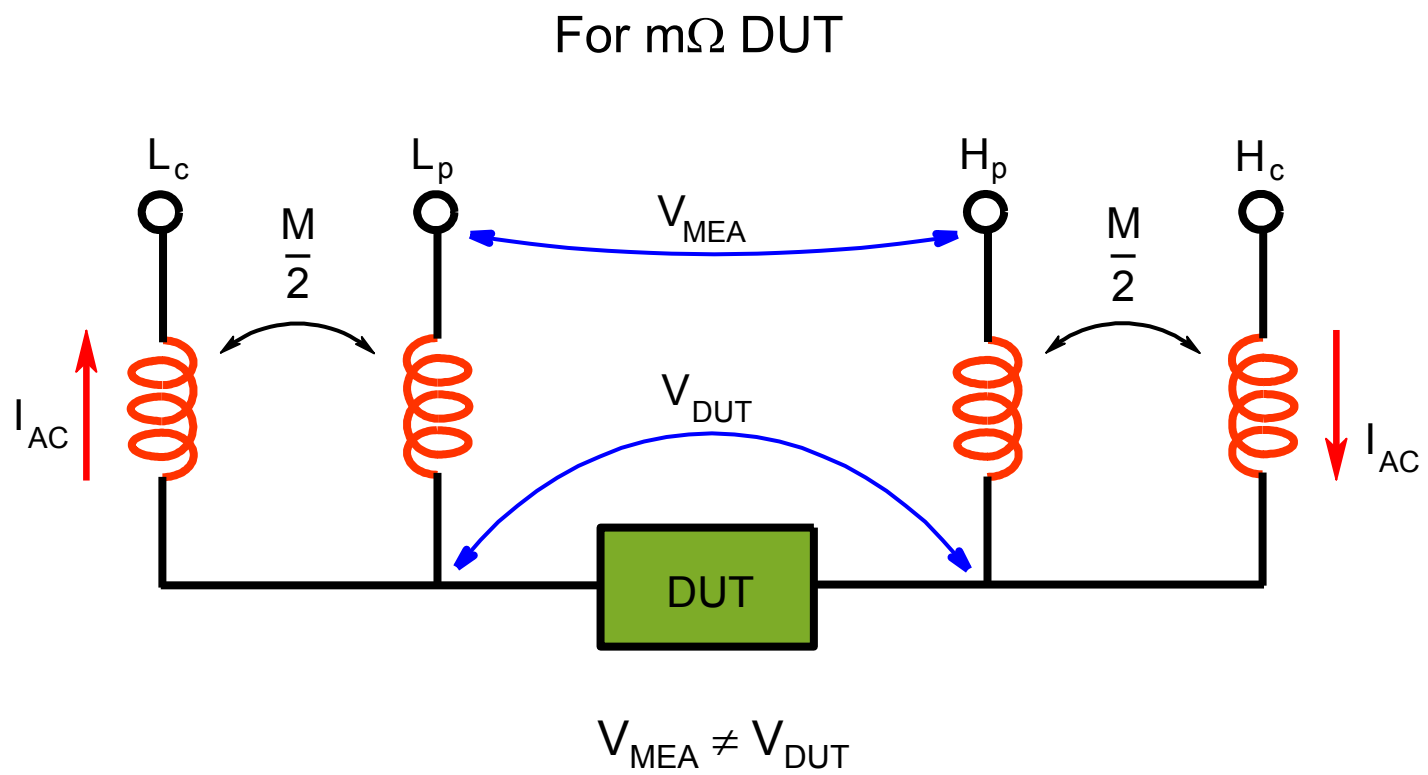


C. 阻抗测量范围 (Ω)

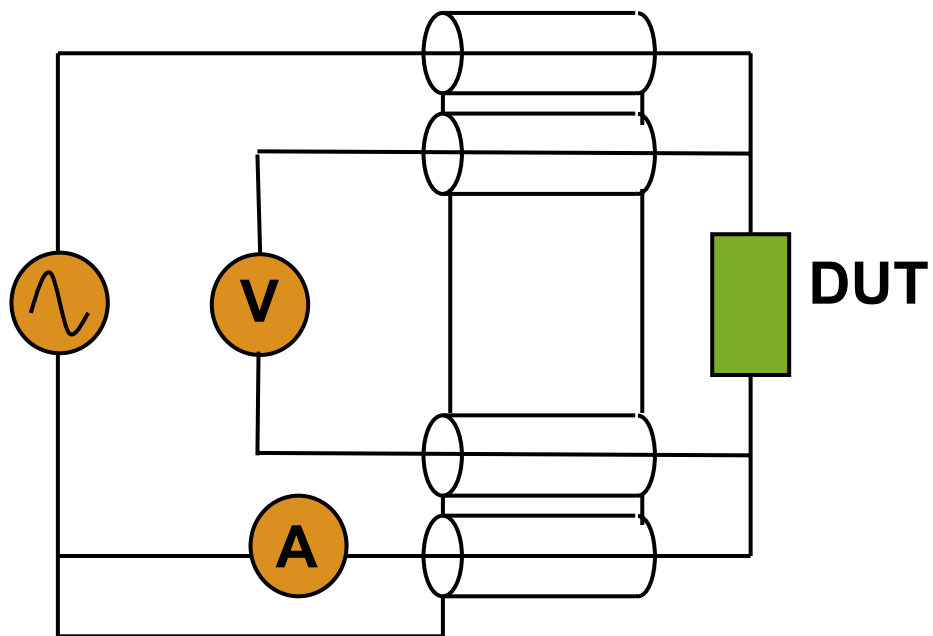


终端配置

- 互感误差

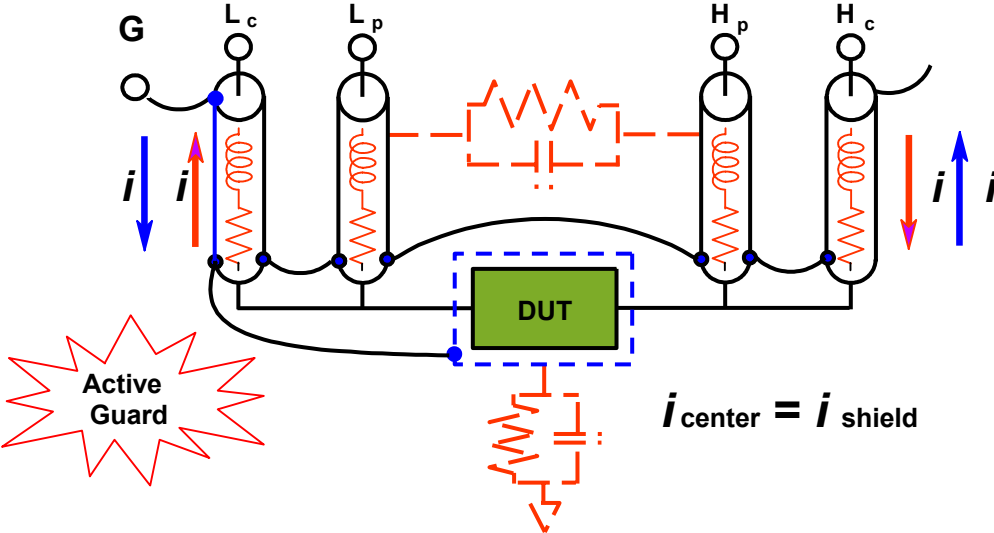


屏蔽4端(4T)连接

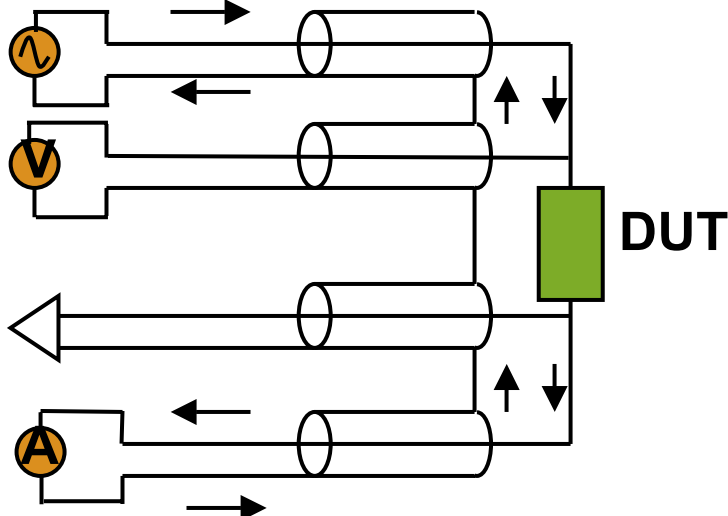


4端对(4TP)连接

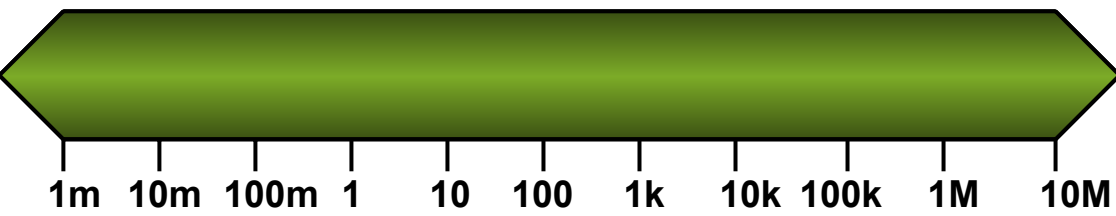
A. 连接



B. 电路

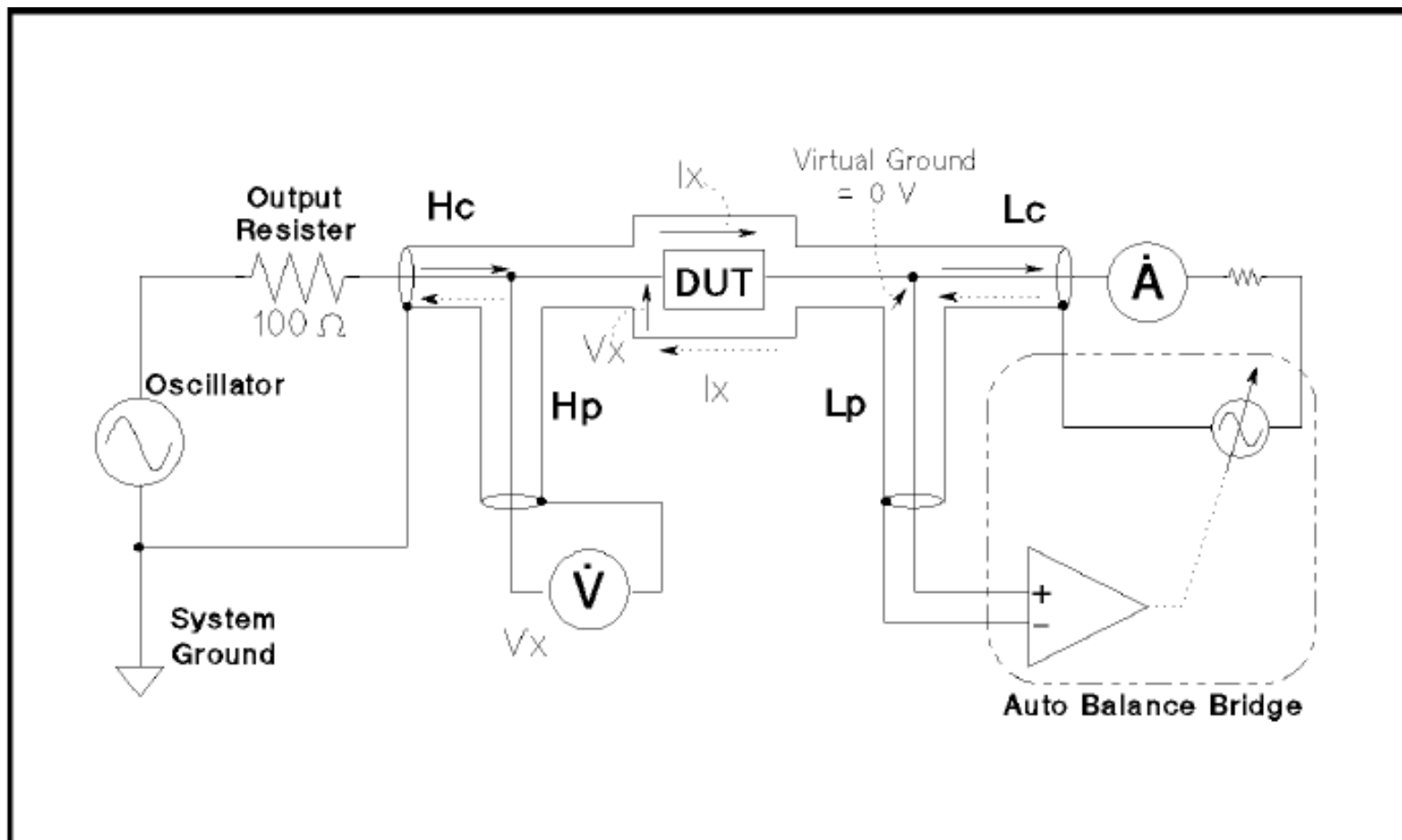


C. 阻抗测量范围 (Ω)



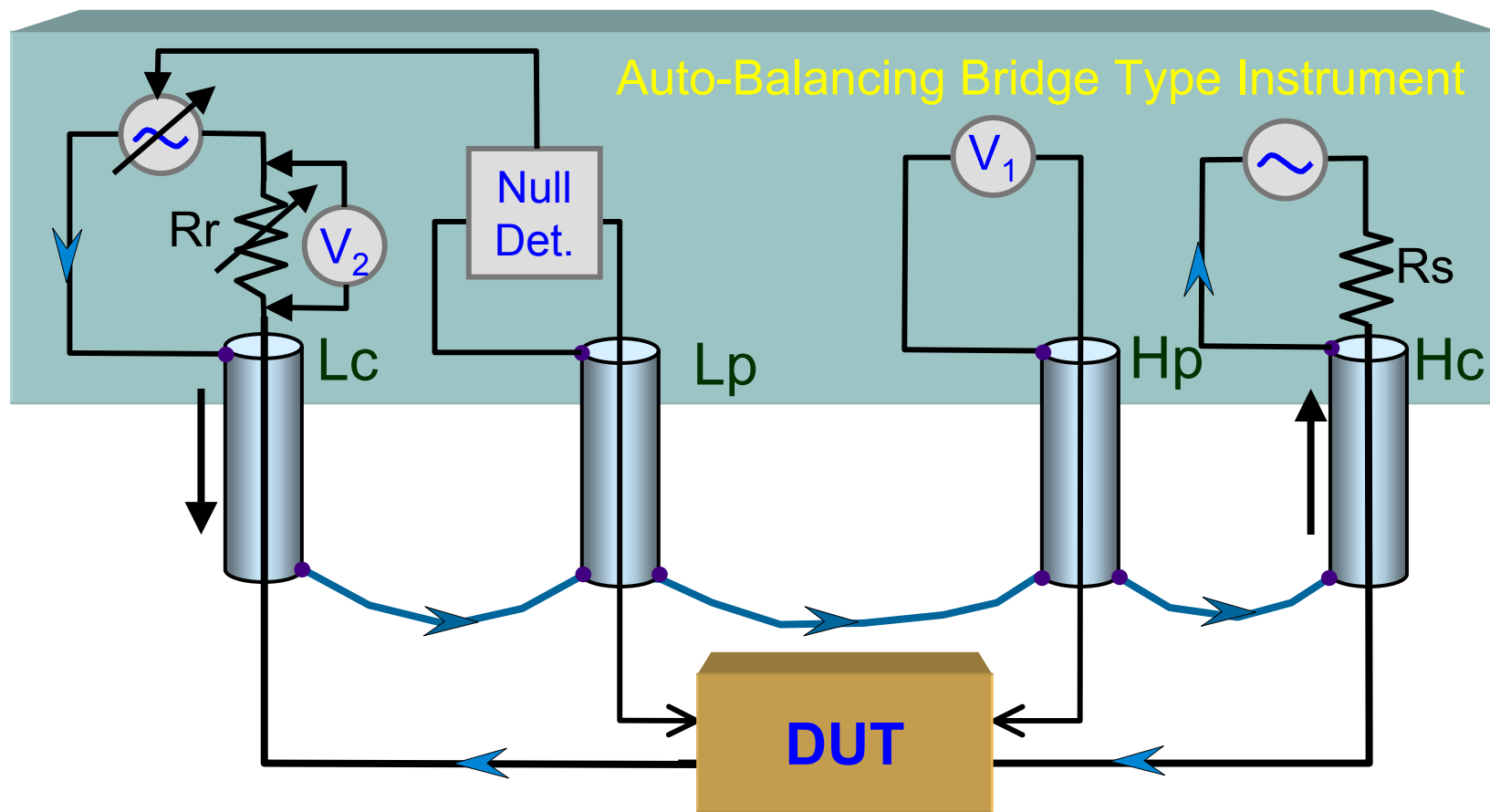
终端配置

- 4端对 (4TP) 简易示意图

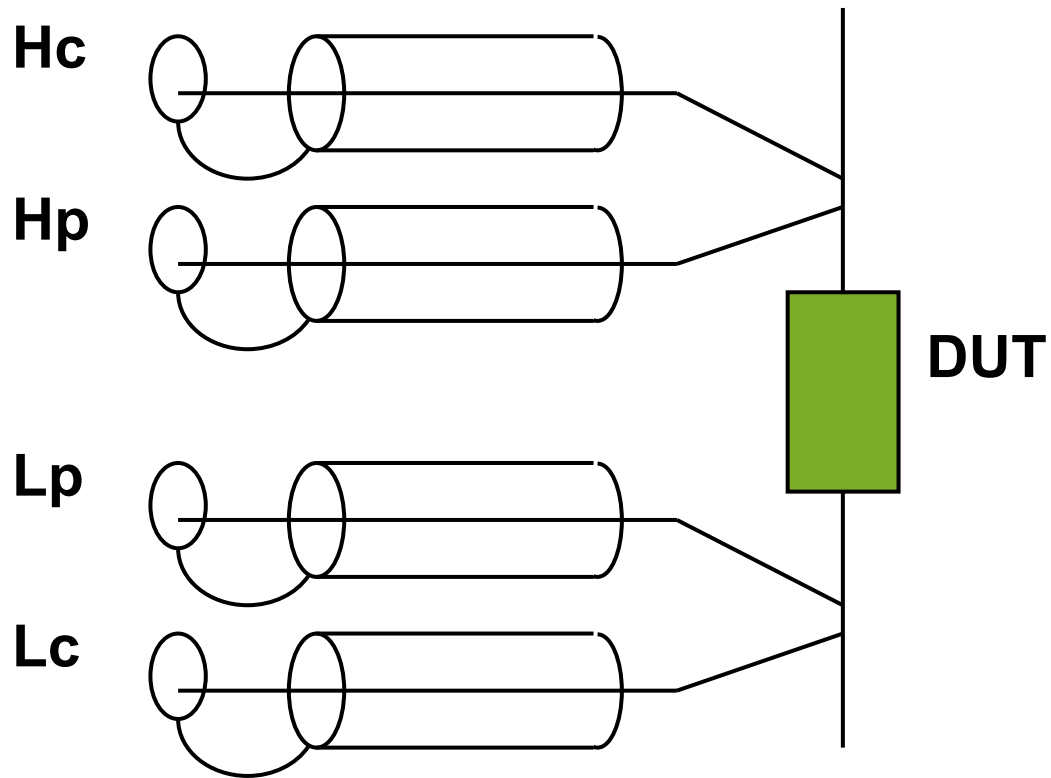


终端配置

- 4端对 (4TP) 简易示意图

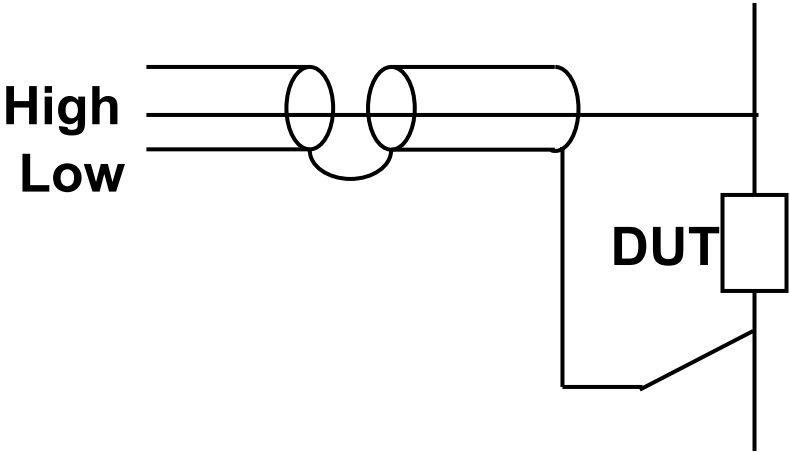


错误连接方法

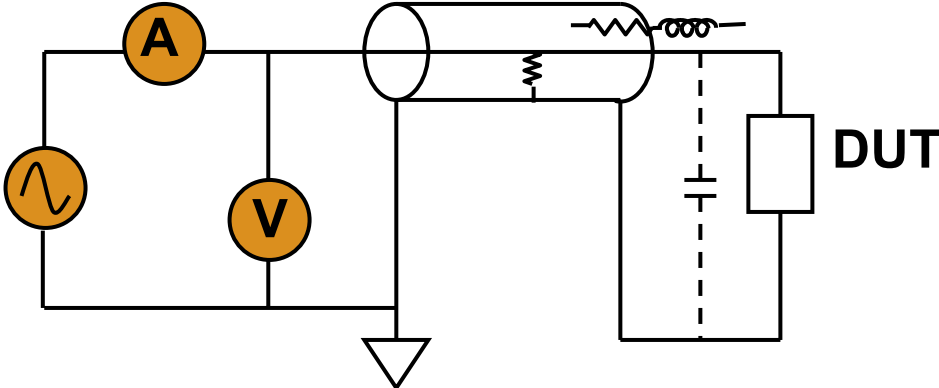


射频终端连接

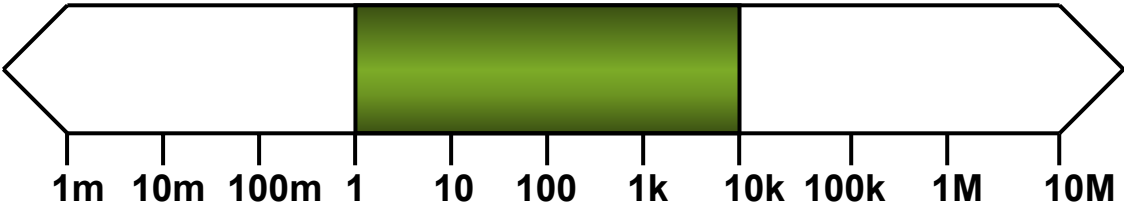
A. 连接方法



B. 电路



C. 阻抗测量范围 (Ω)



电缆长度

$$F \times L \leq 15$$

F = 测量频率 (MHz)

L = 电缆长度 (m)

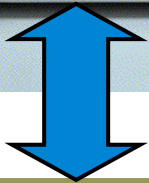
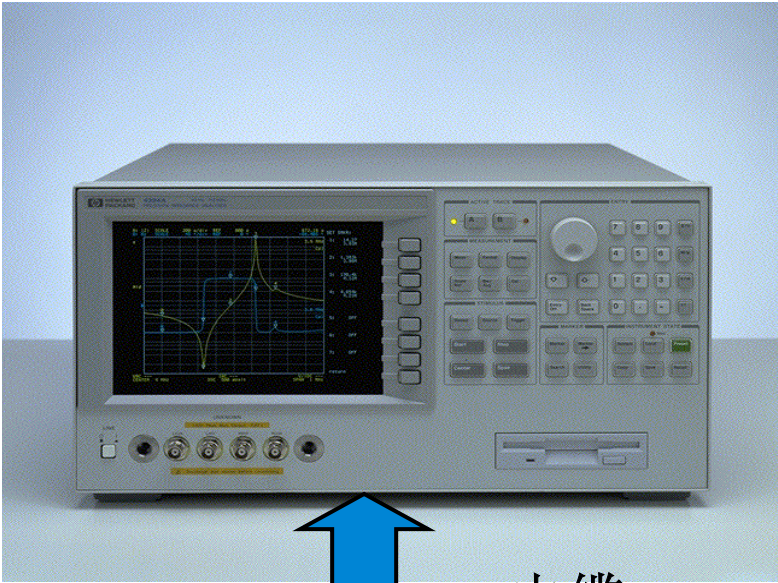
物理意义是: 电缆长度 >> 测试信号波长

4端对测量必须满足电缆长度（或测试频率）限制

如果超过此限制，则无法得到正确的结果（自动平衡电桥无法达到平衡）



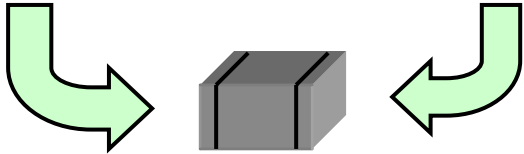
测试夹具



电缆



夹具



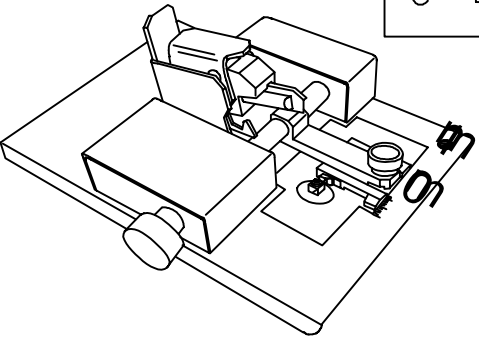
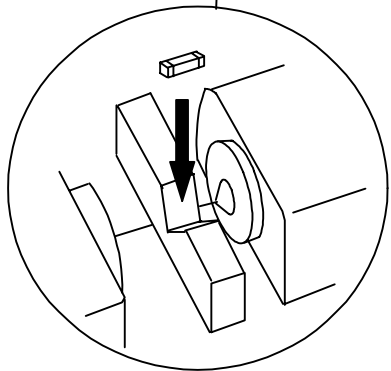
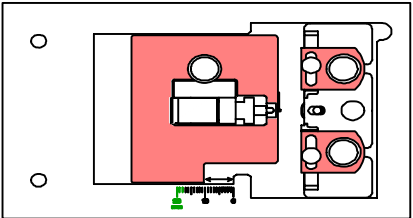
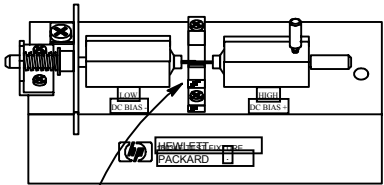
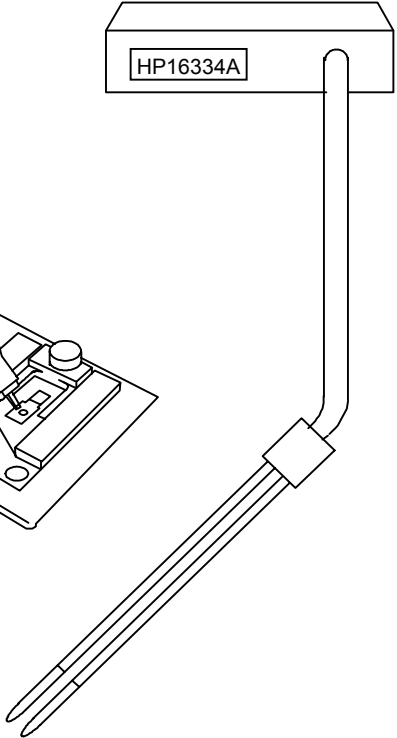
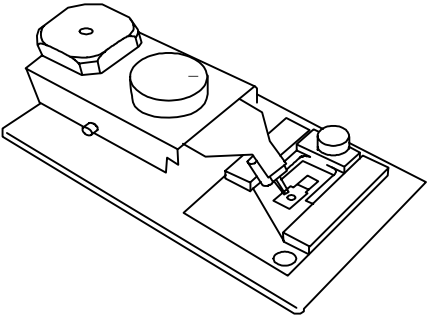
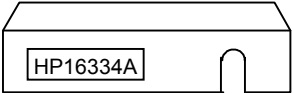
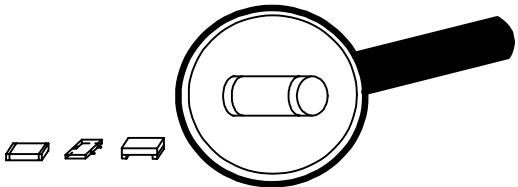
DUT



Agilent Technologies

测试夹具需求

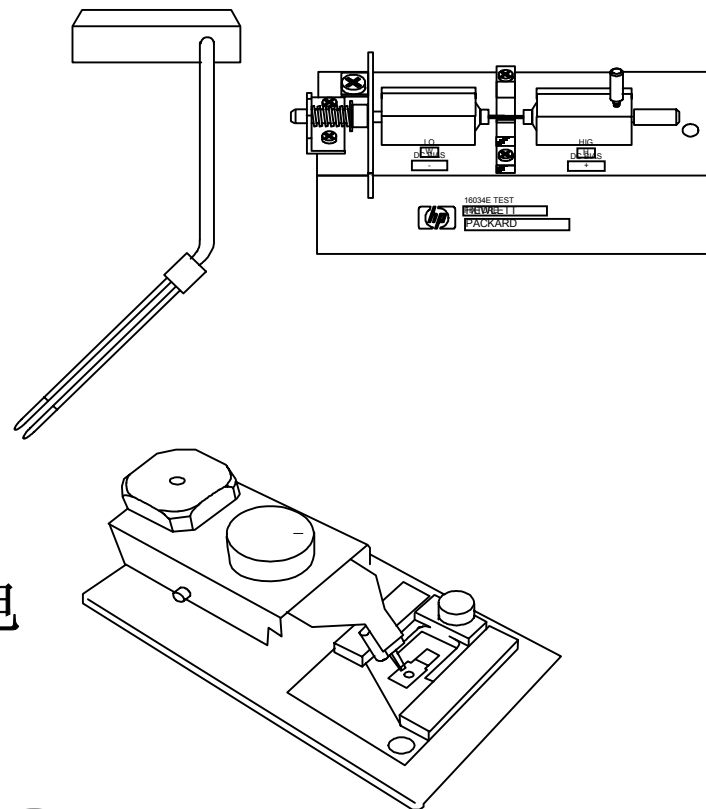
- 残余参数减到最小
- 接触电阻减到最小
- 接触必须可以开路/短路



Agilent 16191A
 Agilent 16192A
 Agilent 16193A
 Agilent 16194A

Agilent 夹具

- **4端对连接**
 - 频率范围上限**110MHz**
 - 与自动平衡电桥仪表配合使用
- **7mm 连接**
 - 频率范围上限**3GHz**
 - 与射频 **RF I-V** 仪表及自动平衡电桥仪表配合使用



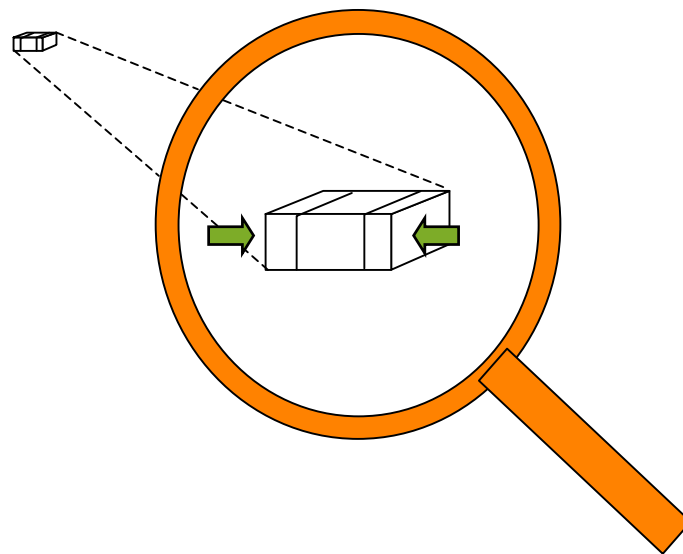
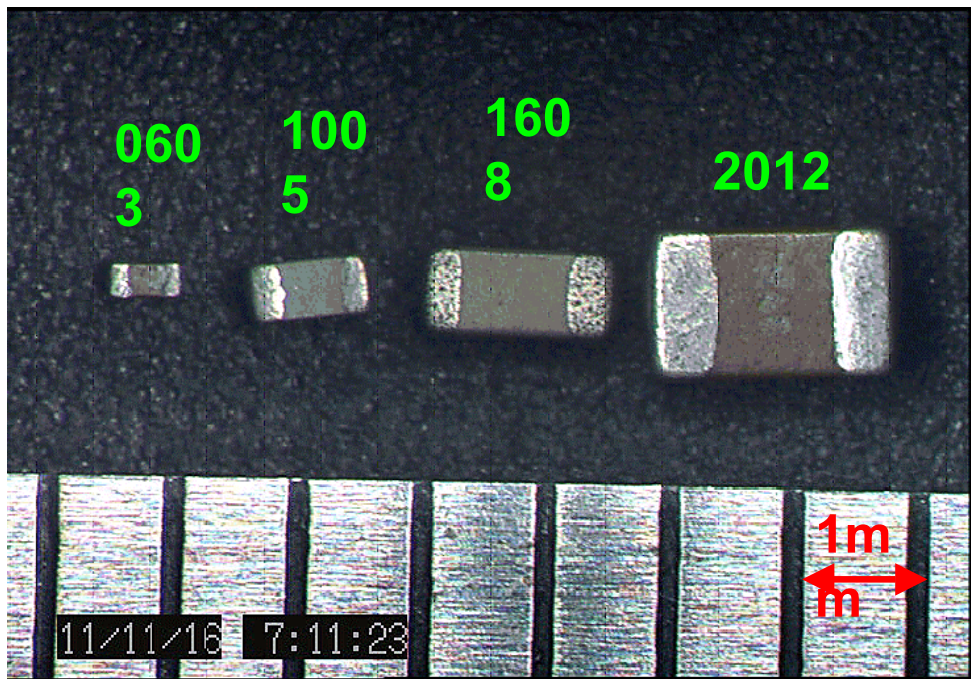
7mm

4TP



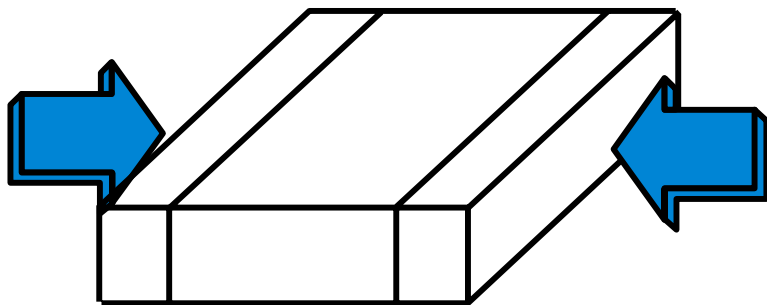
新型 SMD 器件

- 芯片小型化和高性能可以同时存在



SMD 测试夹具 (1)

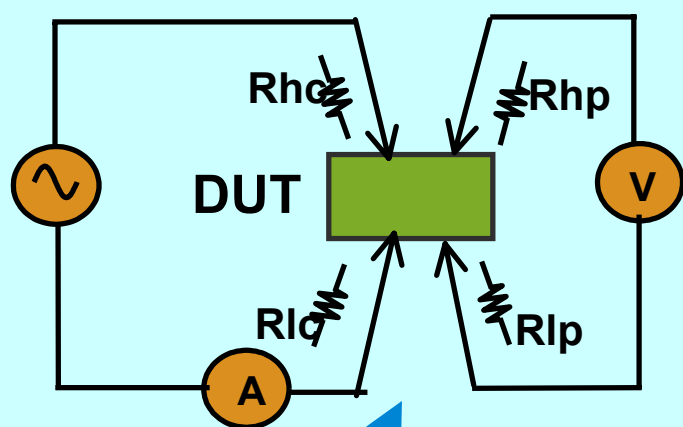
- 良好的电极连接
 - 稳定性
 - 适当的压力
- 接触位置重现性



SMD 测试夹具 (2)

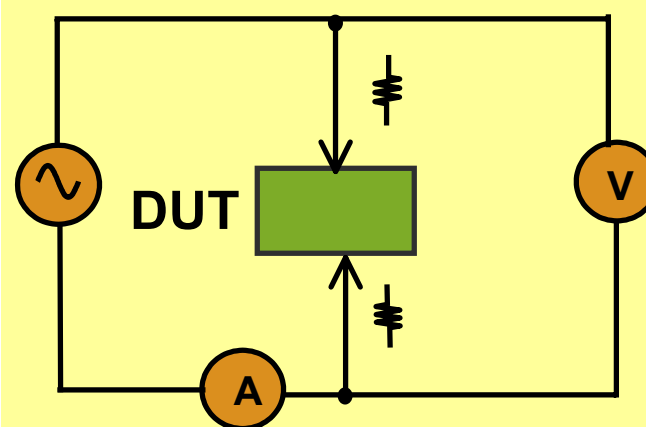
- 低等效串联电阻**ESR**
- **Kelvin** 连接 (4端连接)
- 去除接触电阻效应

Four-Terminal Connection



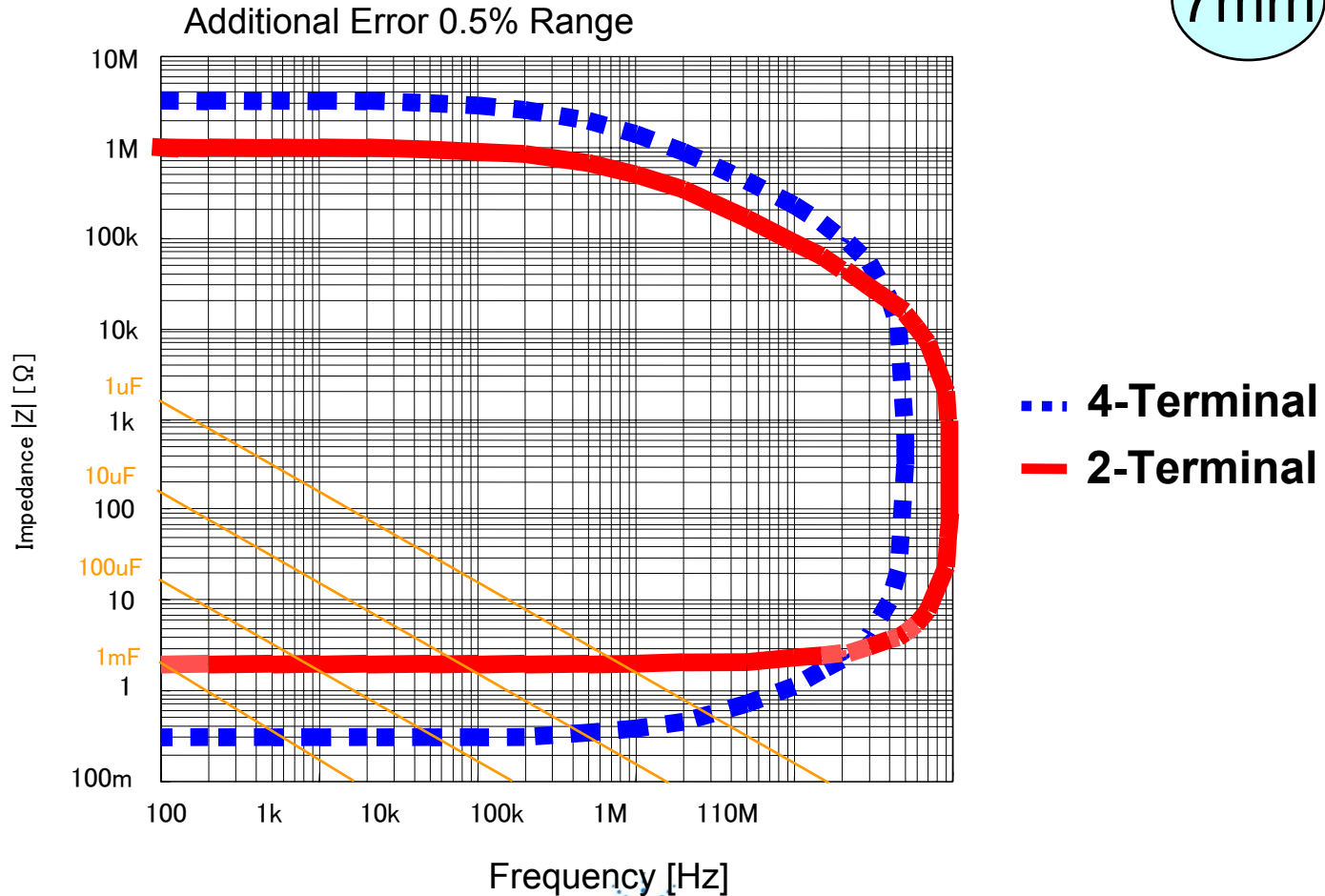
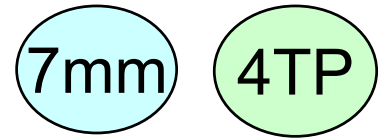
The effect of contact resistance is cancelled

Two-Terminal Connection



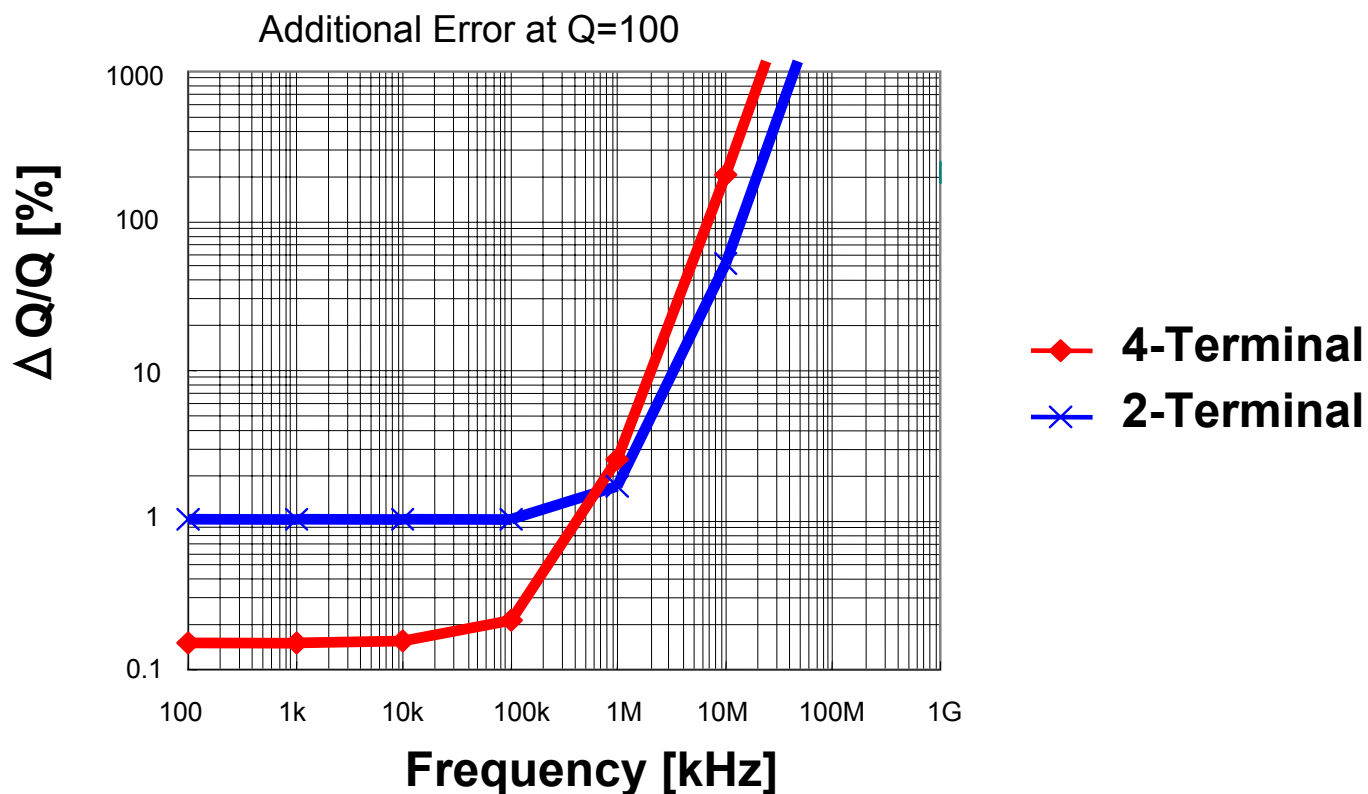
SMD 测试夹具

- 附加误差比较:



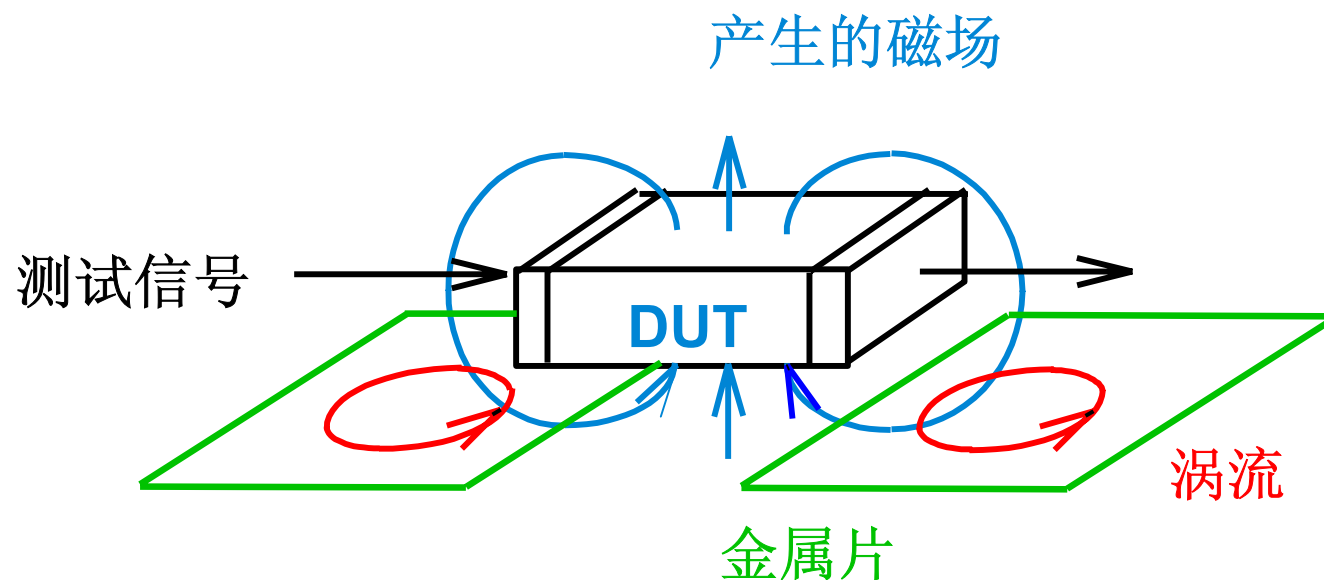
SMD 测试夹具

- 附加误差比较:



SMD 测试夹具 (3)

- **Conductive Parts in DUT Vicinity**

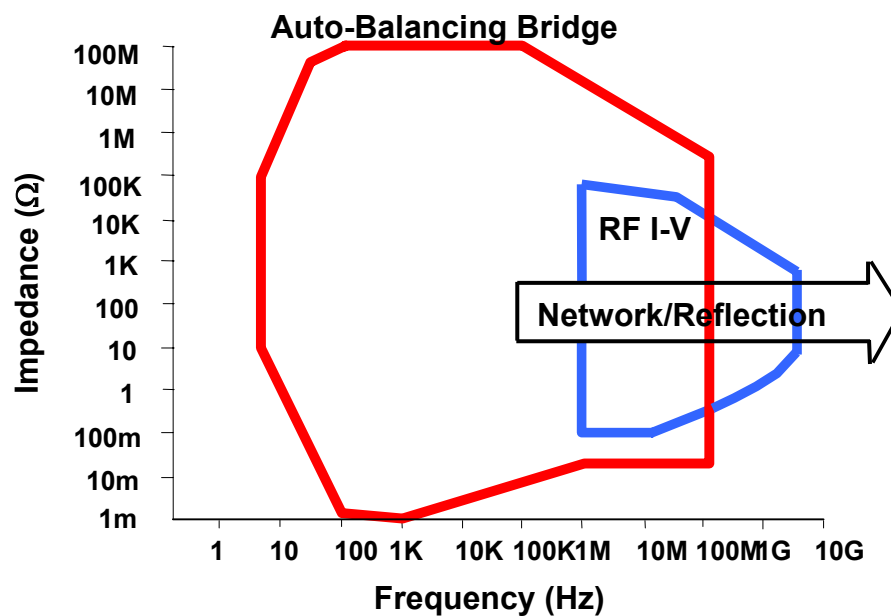


射频测试夹具



内容安排

- 阻抗基础
- 阻抗测量方法
- 夹具和电缆连接
- 校准和补偿
- 总结

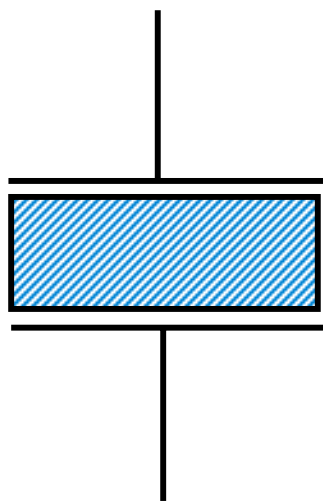


测量误差及补偿

- 测量误差
- 校准和补偿
- 射频范围的校准和补偿



真值

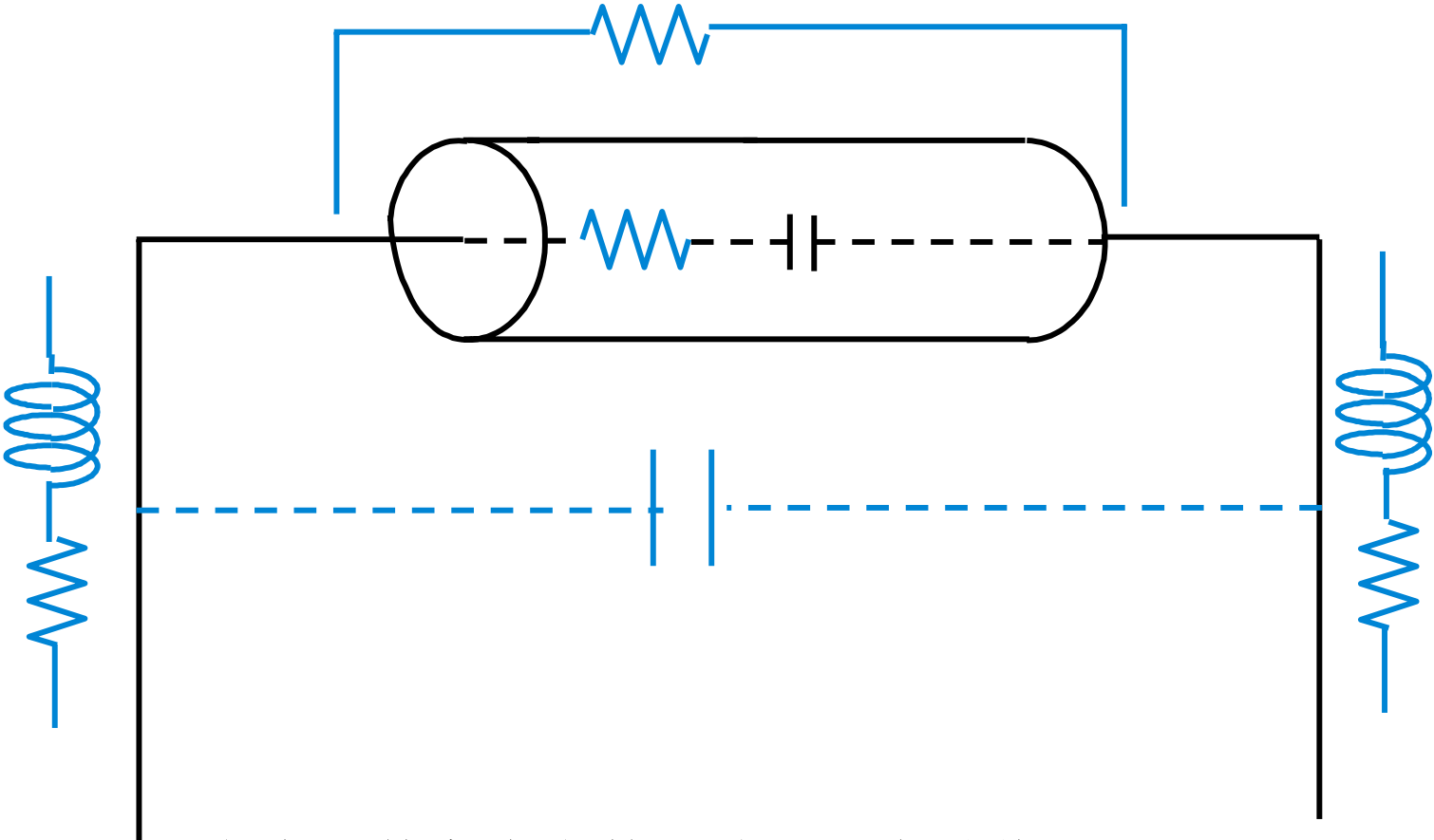


$$C = K\epsilon_0 \frac{A}{d}$$

排除寄生参数缺陷的电路元件。
真值可以由元件所含物理成分的数学关系确定。

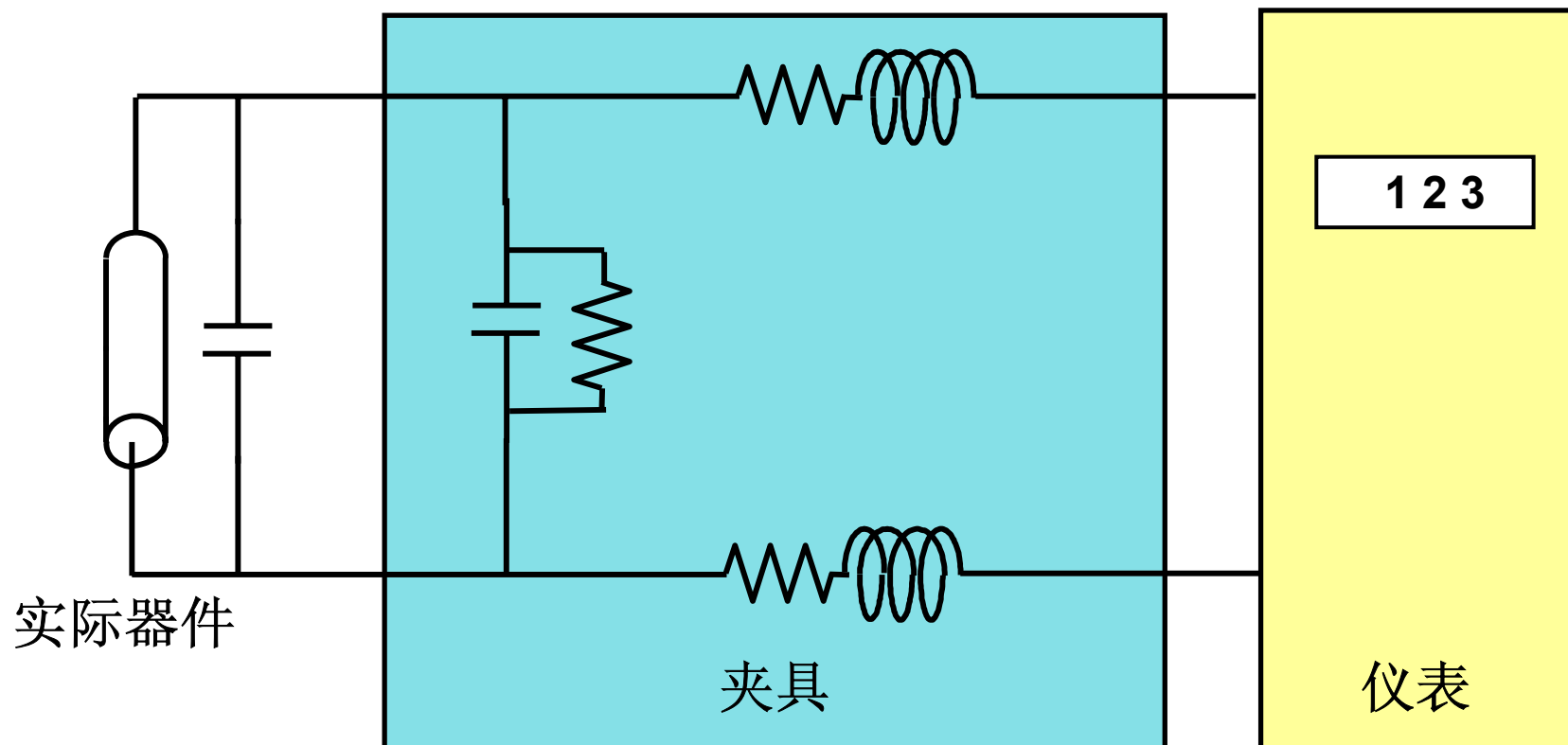


有效值



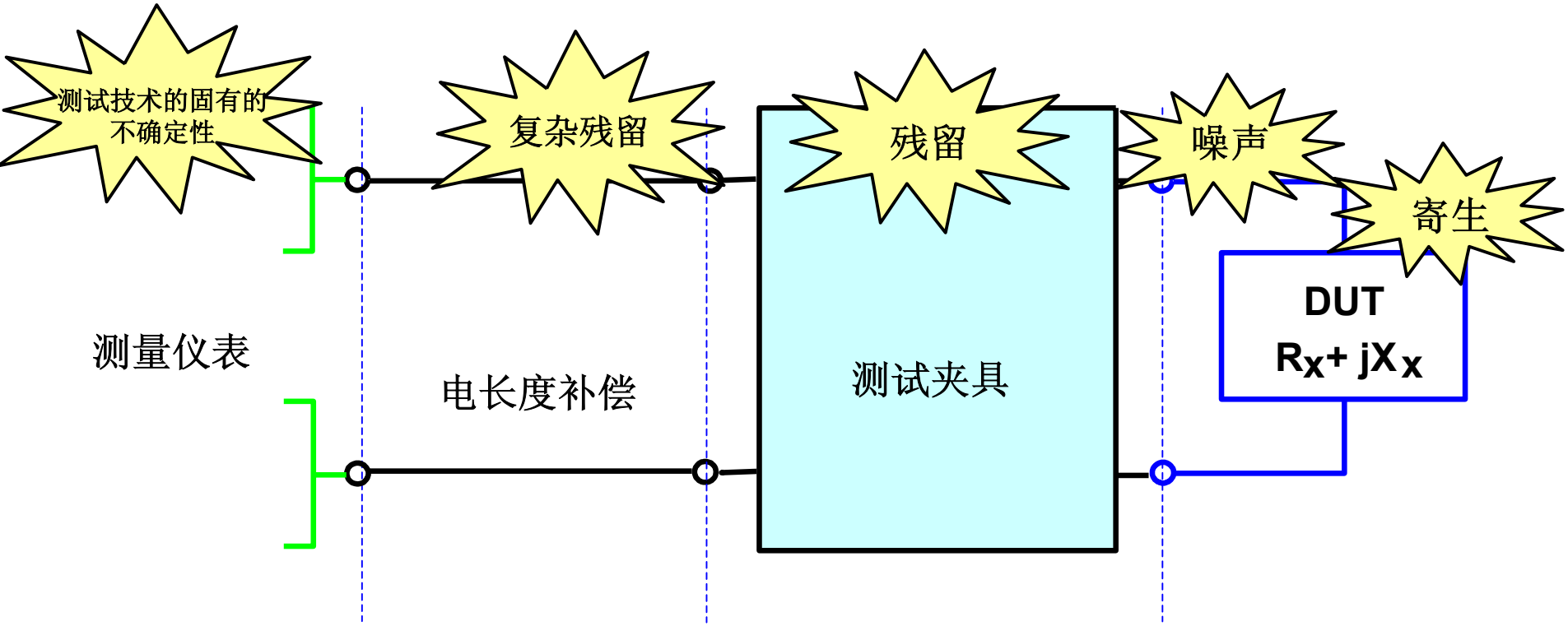
考虑元件寄生参数影响——有效值

指示值



指示值——仪器仪表获取和显示的量值。
与真值和有效值相比，指示值总存在误差。

测量误差源

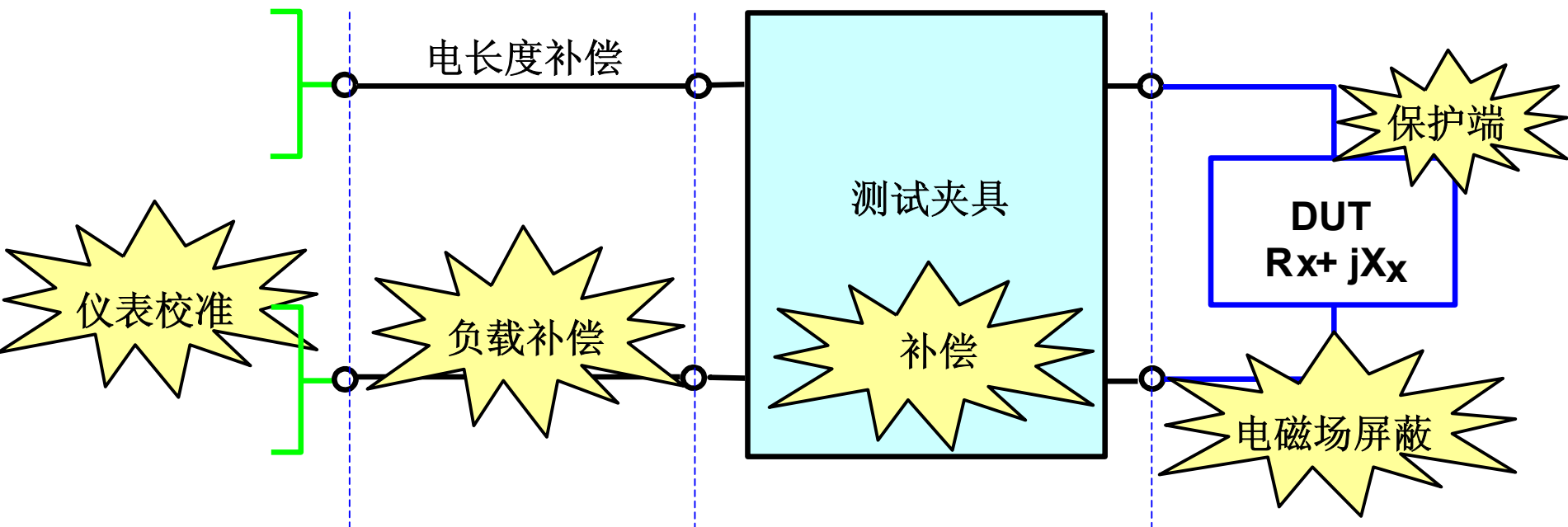


测量误差

- 仪表固有的测量不准确度
- 测试夹具和测试电缆的残留阻抗
- 环境噪声

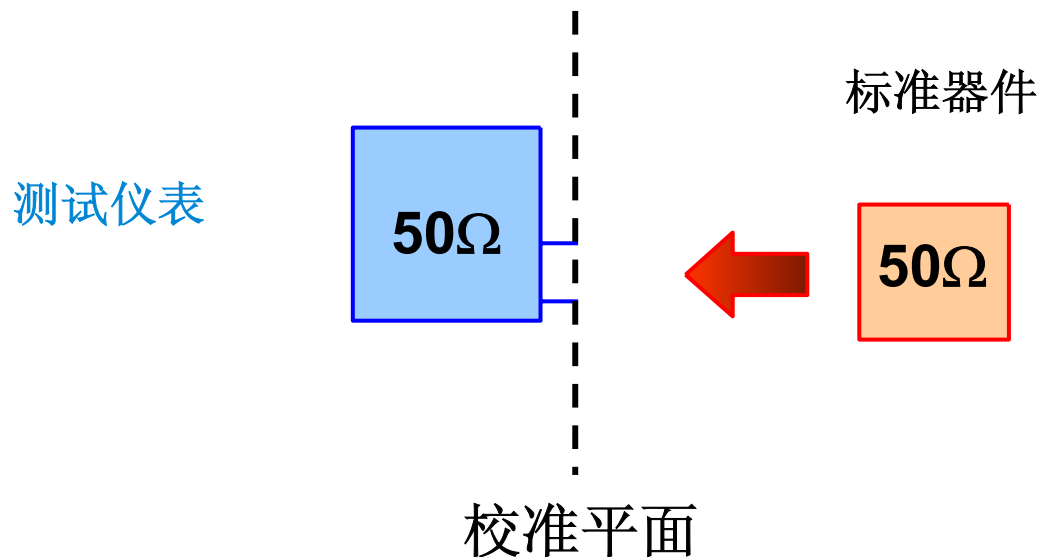


针对测量误差极限的对策



什么是校准?

- 校准平面的定义：在校准平面上能得到规定的测量精度（测试结果可以溯源）

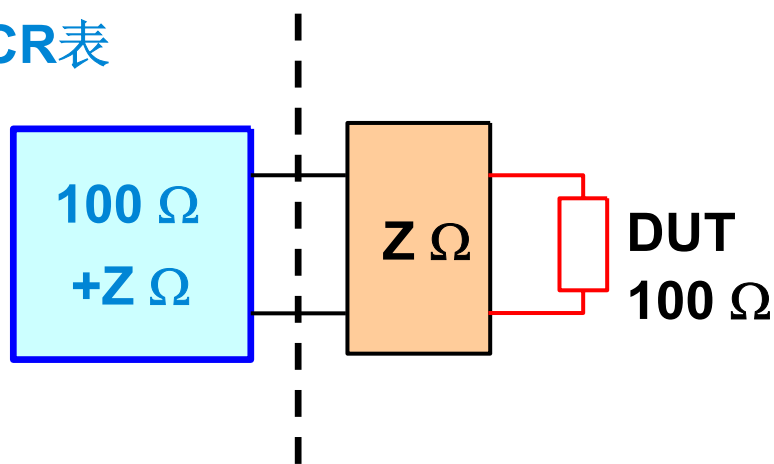


补偿的定义

- 补偿是为了减小**DUT**与仪器校准平面间的误差源的影响。
- 补偿不能完全消除误差——补偿后的精度也达不到校准平面上的精度

阻抗分析仪
或
LCR表

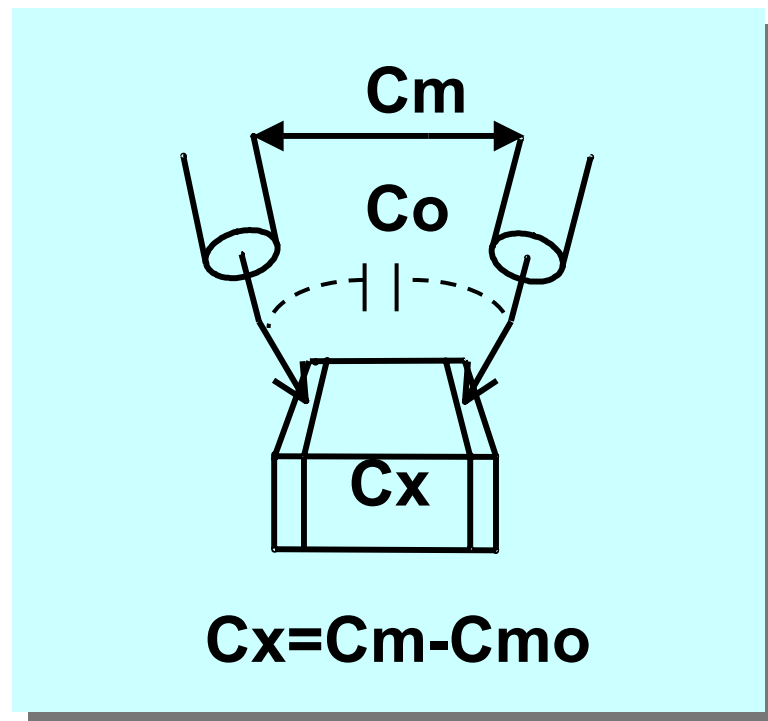
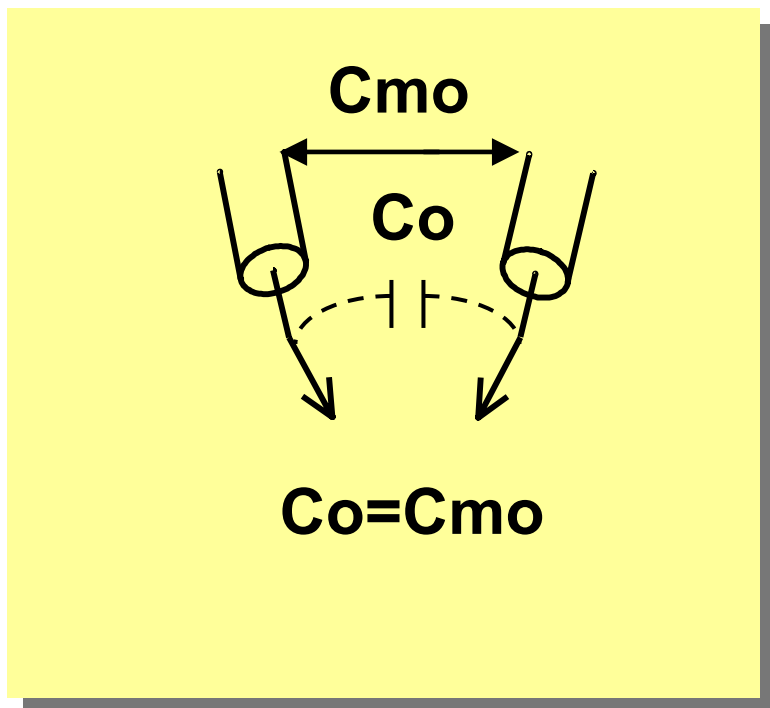
夹具, 电缆



- **OFFSET**补偿
- **OPEN/SHORT** 补偿
- **OPEN/SHORT/LOAD**补偿

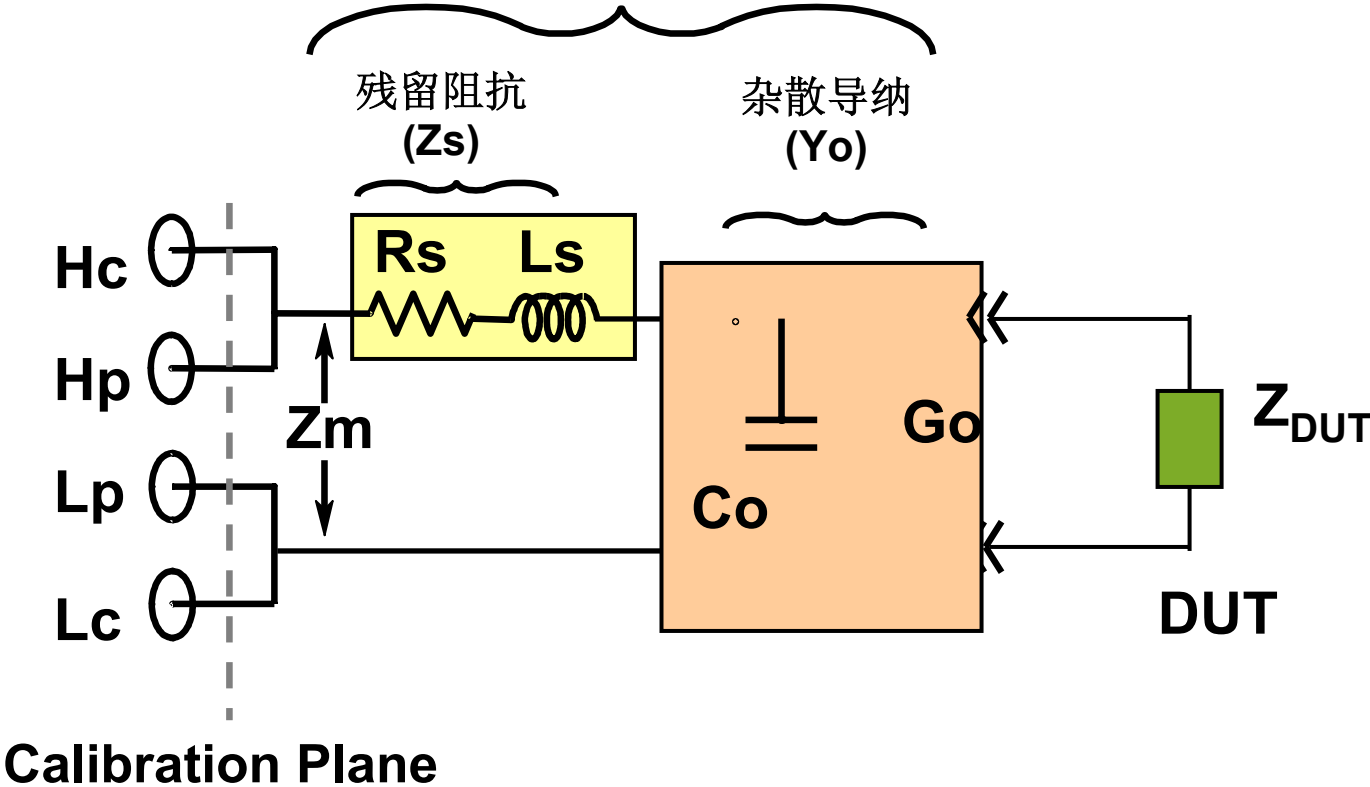


OFFSET 补偿

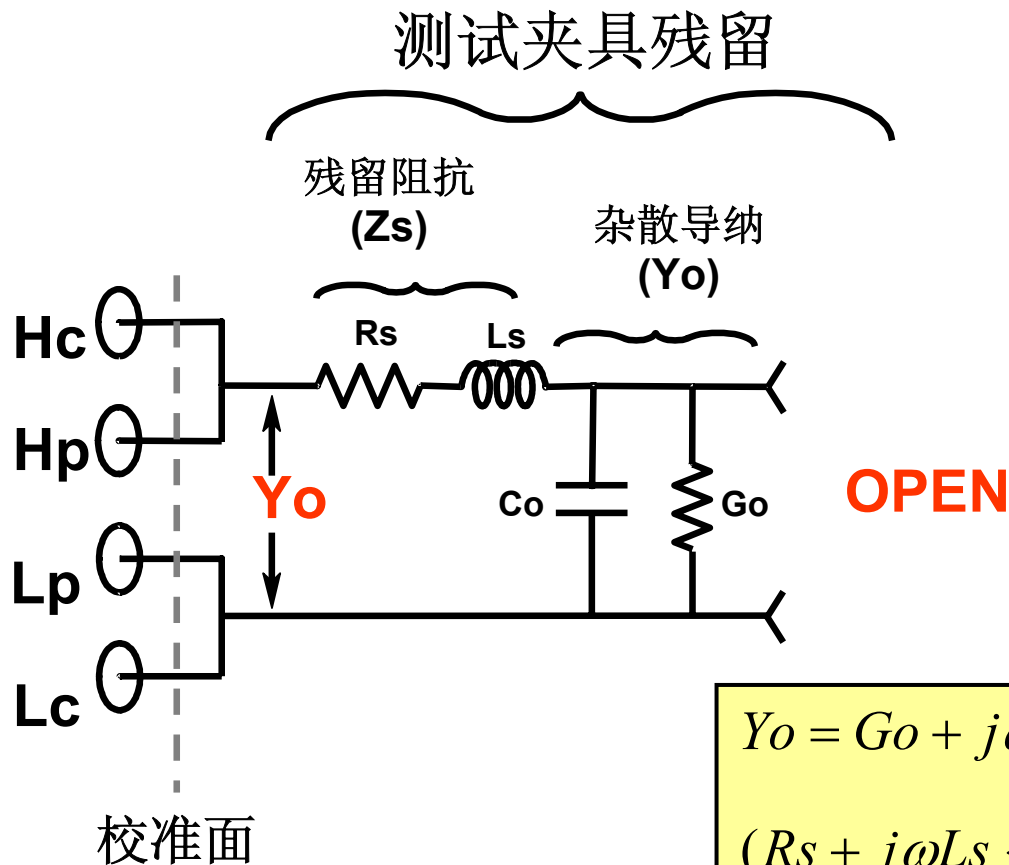


OPEN/SHORT 补偿

测试夹具残留



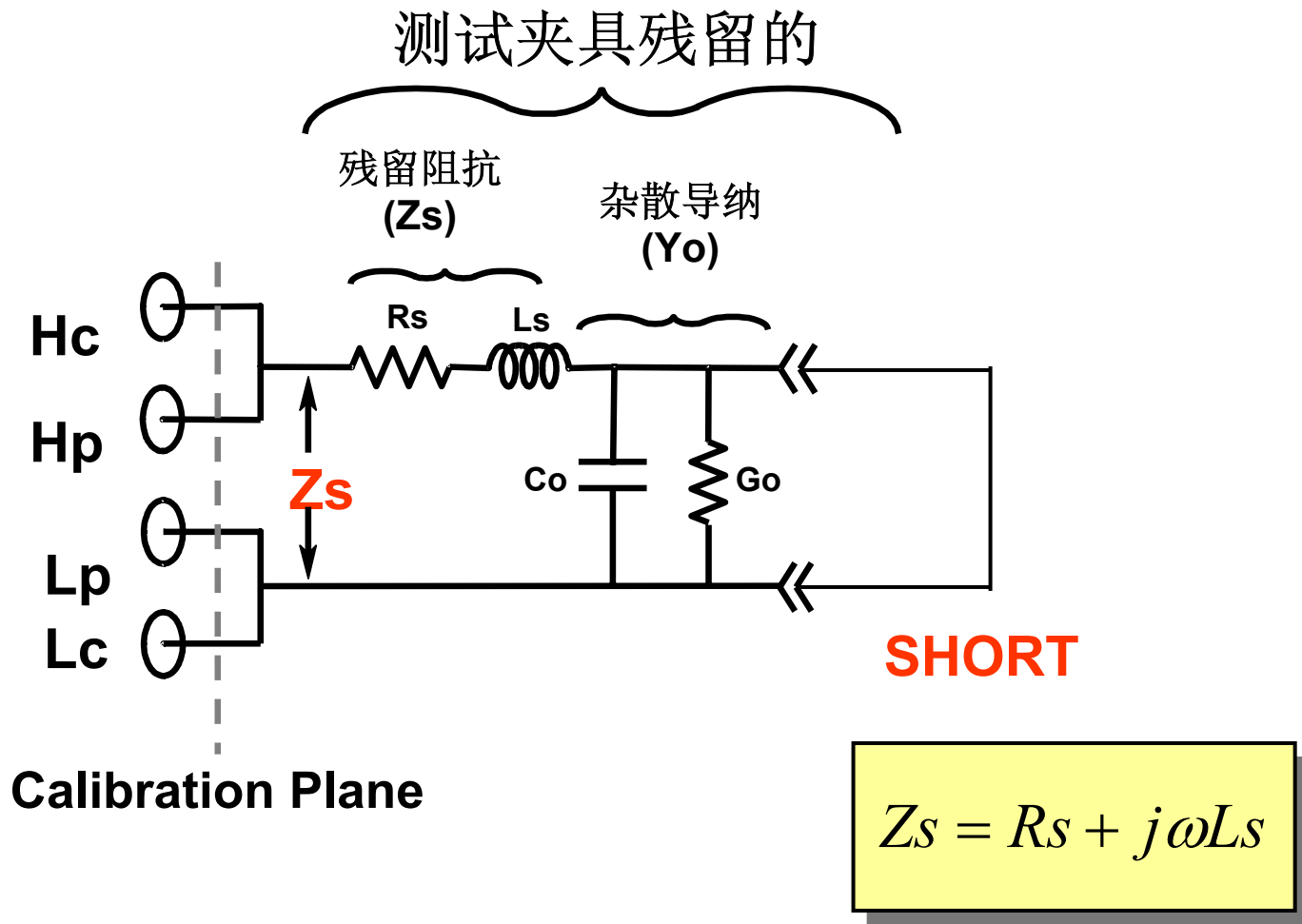
OPEN/SHORT 补偿 (开路)



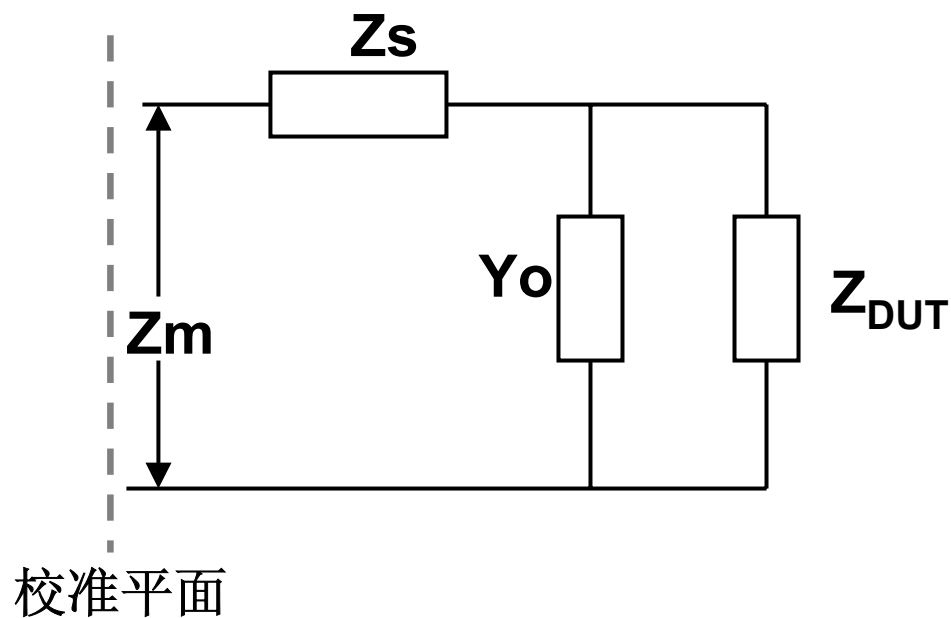
$$Y_o = G_o + j\omega C_o$$

$$(R_s + j\omega L_s \ll \frac{1}{G_o + j\omega C_o})$$

OPEN/SHORT 补偿 (短路)



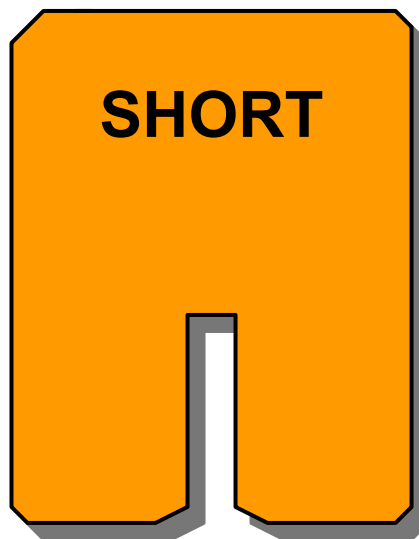
OPEN/SHORT 补偿



$$Z_{DUT} = \frac{Z_m - Z_s}{1 - (Z_m - Z_s)Y_o}$$



OPEN/SHORT 补偿的注意事项

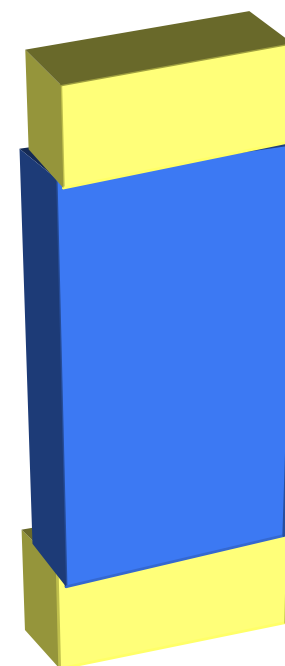


1mΩ



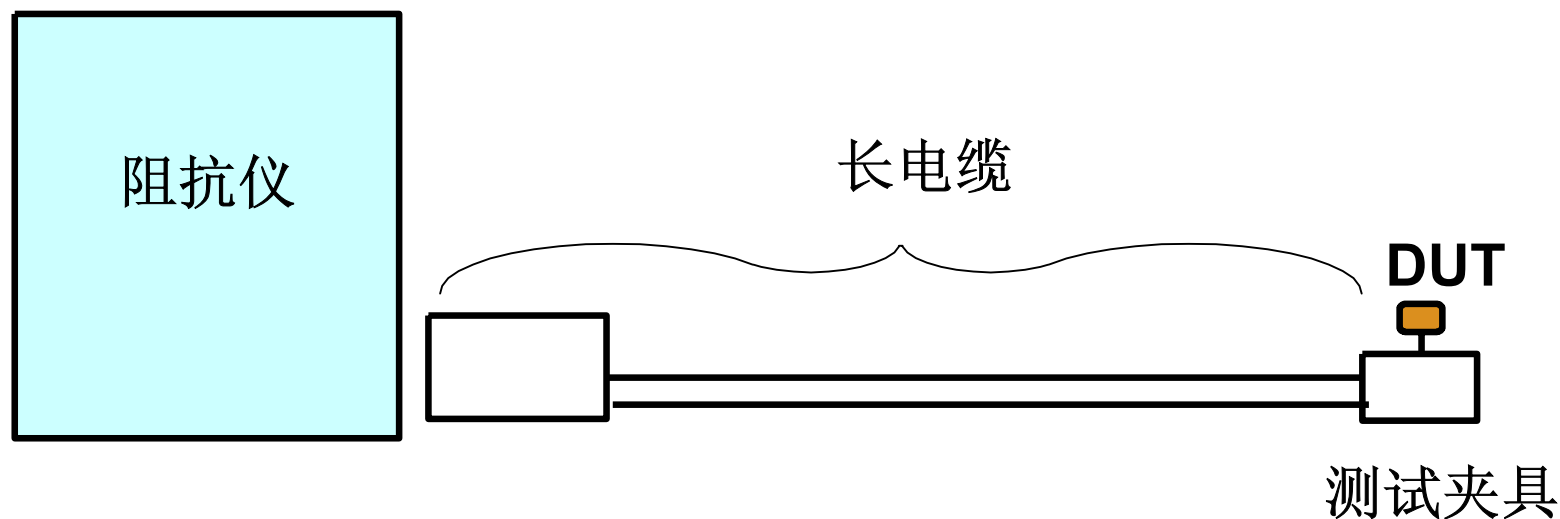
OPEN/SHORT/LOAD 补偿

- 减少复杂残余量
- 排除相移误差
- 提高不同仪表之间的相关性



OPEN/SHORT/LOAD 补偿举例

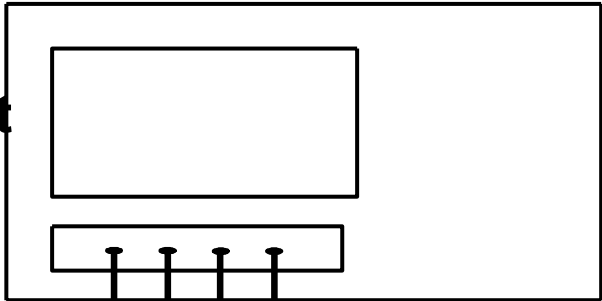
- 去除由于相移造成的误差



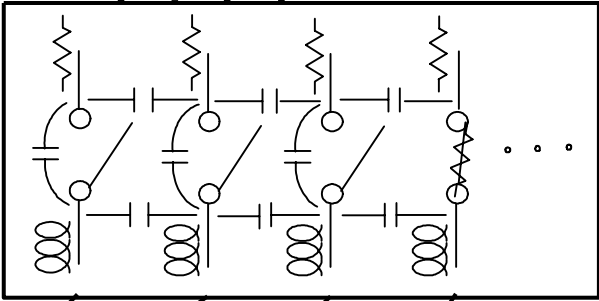
OPEN/SHORT/LOAD 补偿举例

- 存在复杂的残留阻抗

• Instrument

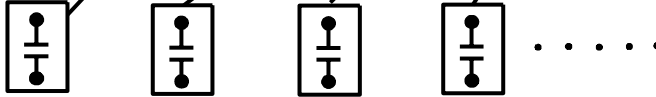


• Scanner



Complex Residuals

• DUTs



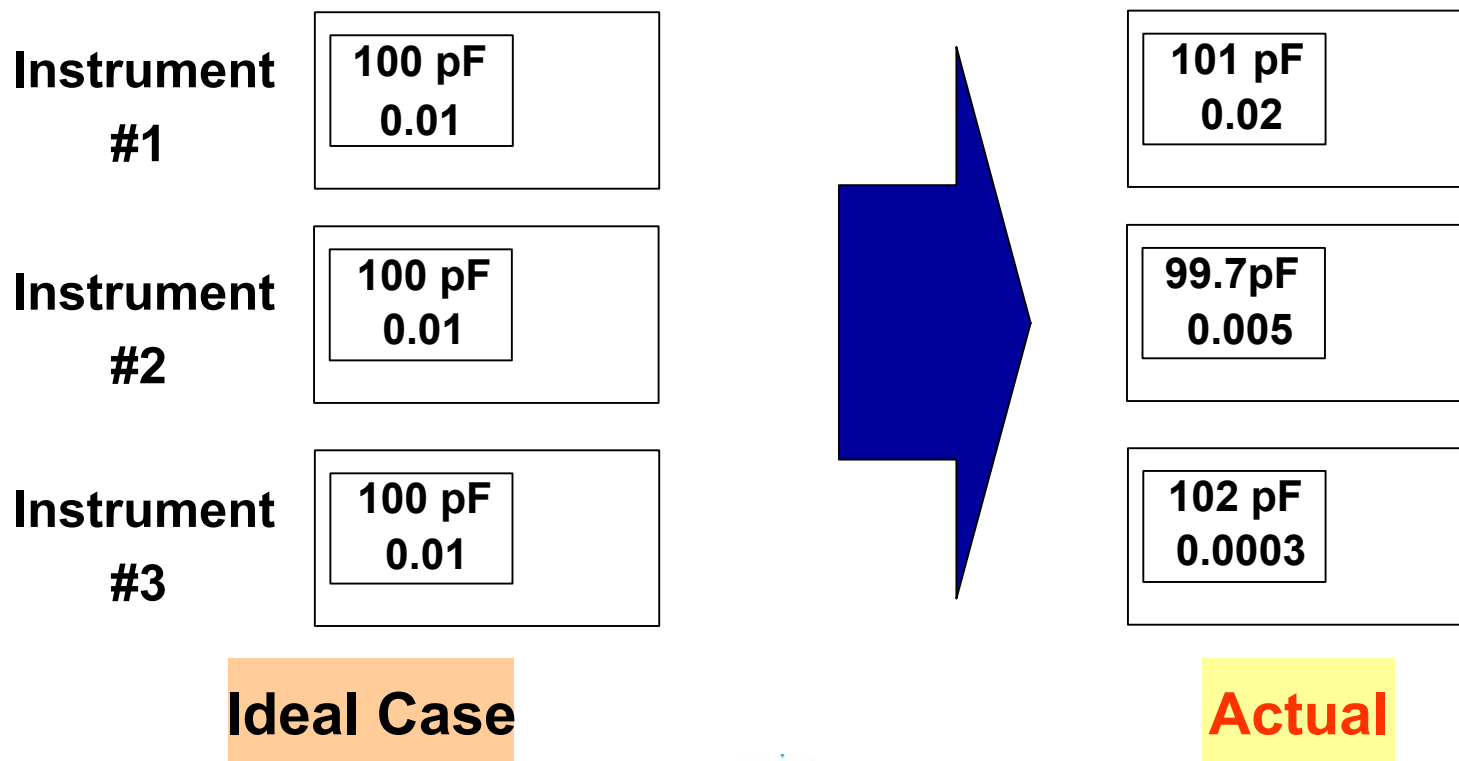
杂散电容

残留电感

残留电阻

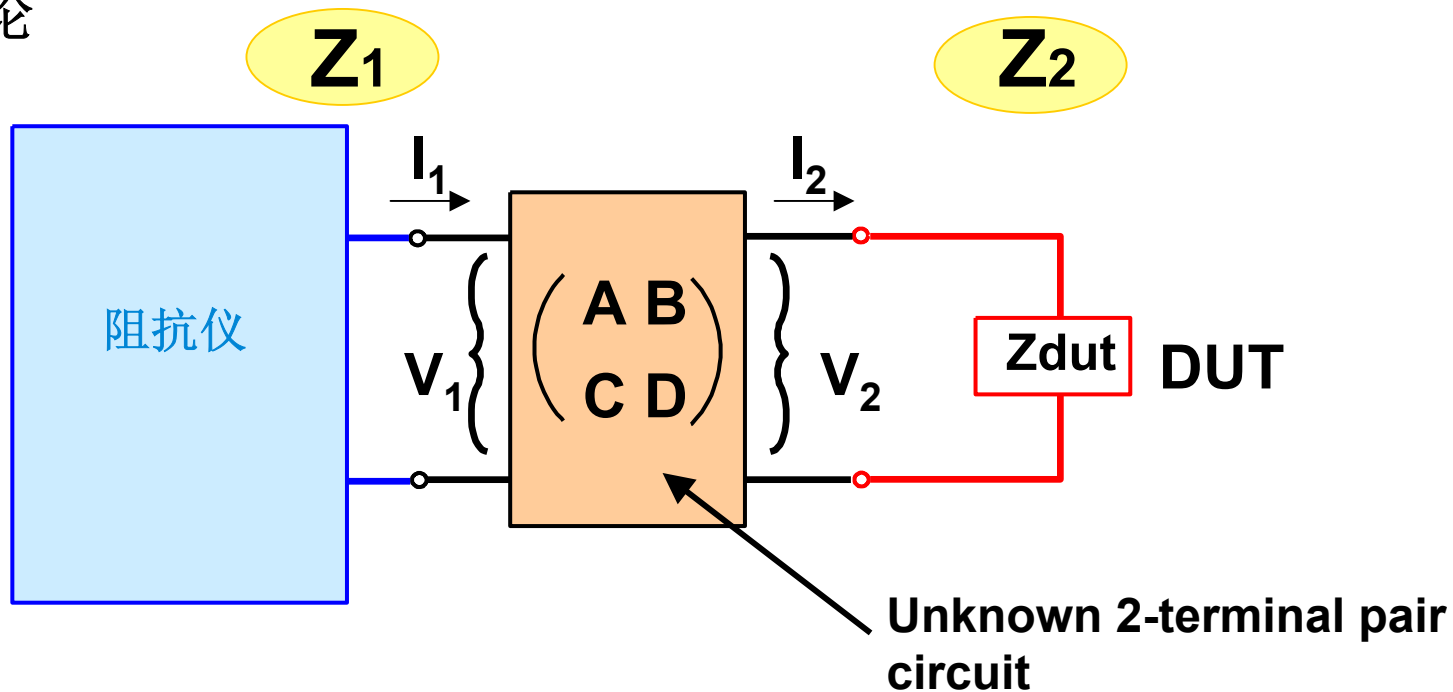
OPEN/SHORT/LOAD 补偿举例

- 仪表之间没有相关性— 因此测试结果存在差异



OPEN/SHORT/LOAD 补偿

- 基本理论

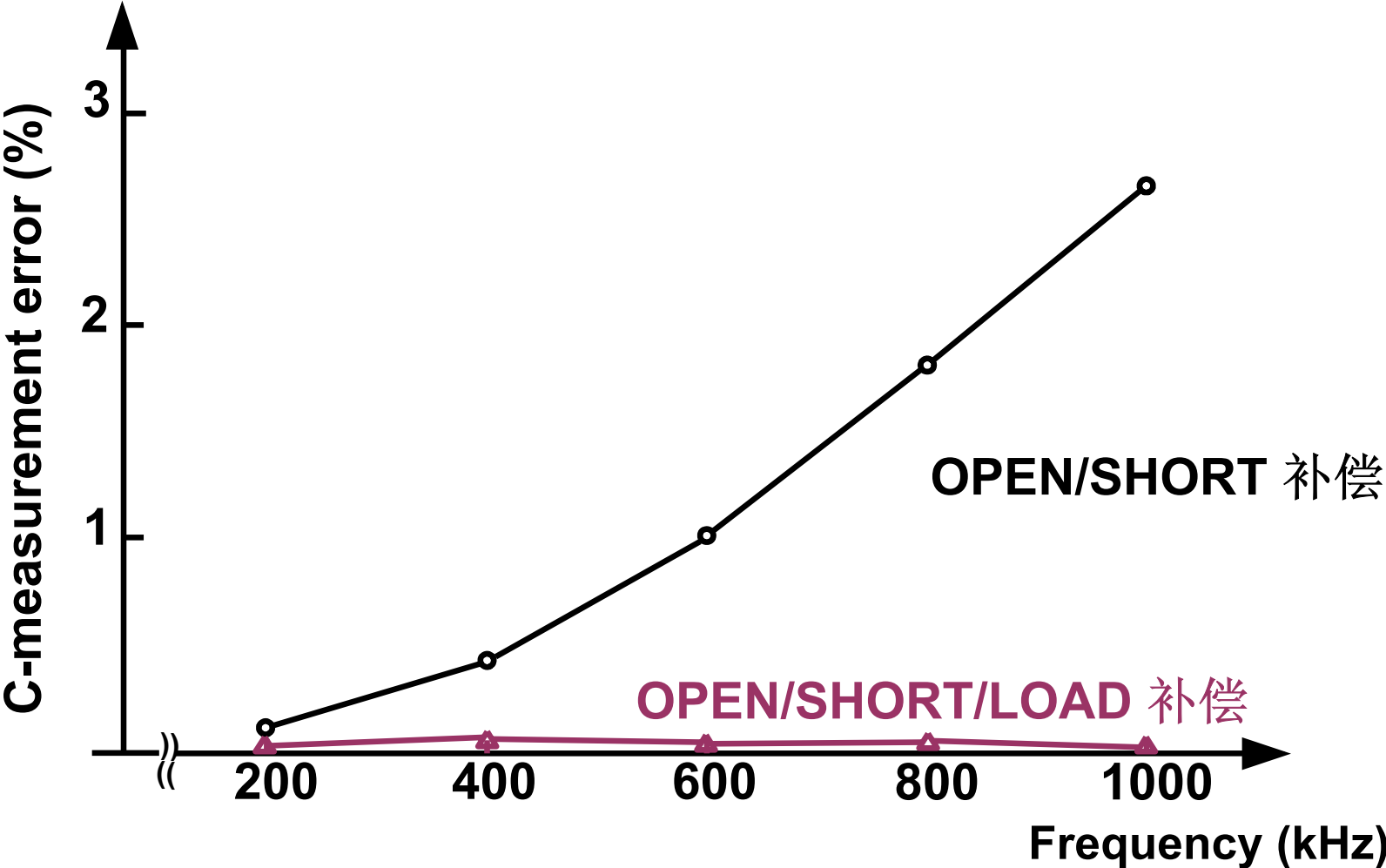


$$Z_1 = \frac{AV_2 + BI_2}{CV_2 + DI_2} = \frac{AZ_2 + B}{CZ_2 + D}$$

$$Z_1 = \frac{V_1}{I_1}, \quad Z_2 = \frac{V_2}{I_2}$$



OPEN/SHORT/LOAD 补偿效果



补偿负载器件选择

- 当测量很宽阻抗范围的**DUT**, 选择**100Ω – 1kΩ** 阻抗作负载
- 当测量仅有一个阻抗值的**DUT**, 选择与**DUT**阻抗值约接近的器件为补偿负载
- 采用纯且稳定的电容或电阻伪补偿负载
- 负载值必须明确已知



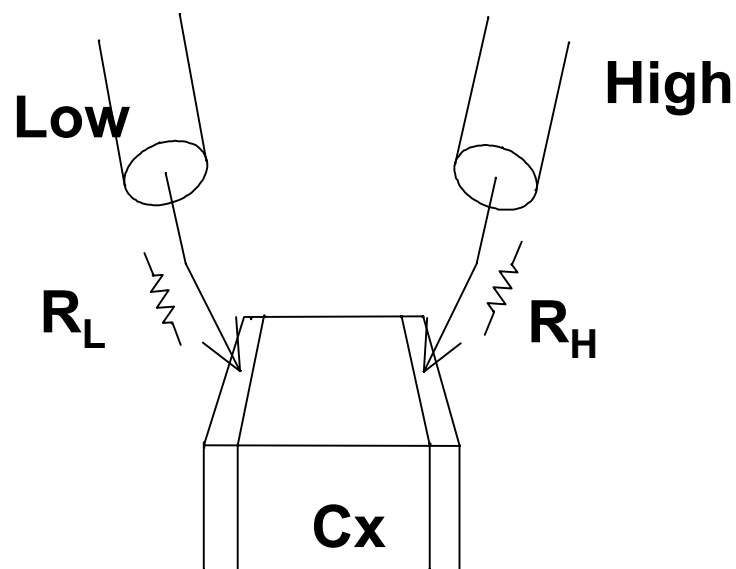
OPEN/SHORT/LOAD 补偿限制

- 开路值必须远远大于被测器件**DUT**阻抗 (>100 倍)
- 短路值必须远远小于被测器件**DUT**阻抗值 ($<1/100$)



误差

- 接触电阻——2端(2T)连接

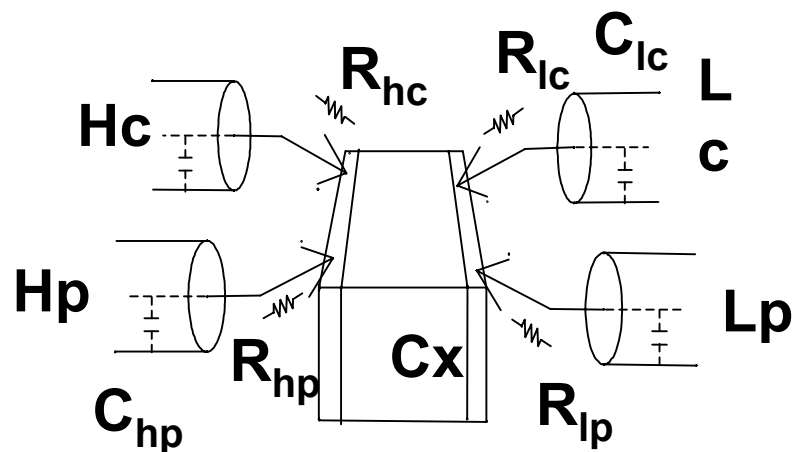


$$D_{error} = \omega C_X (R_L + R_H)$$



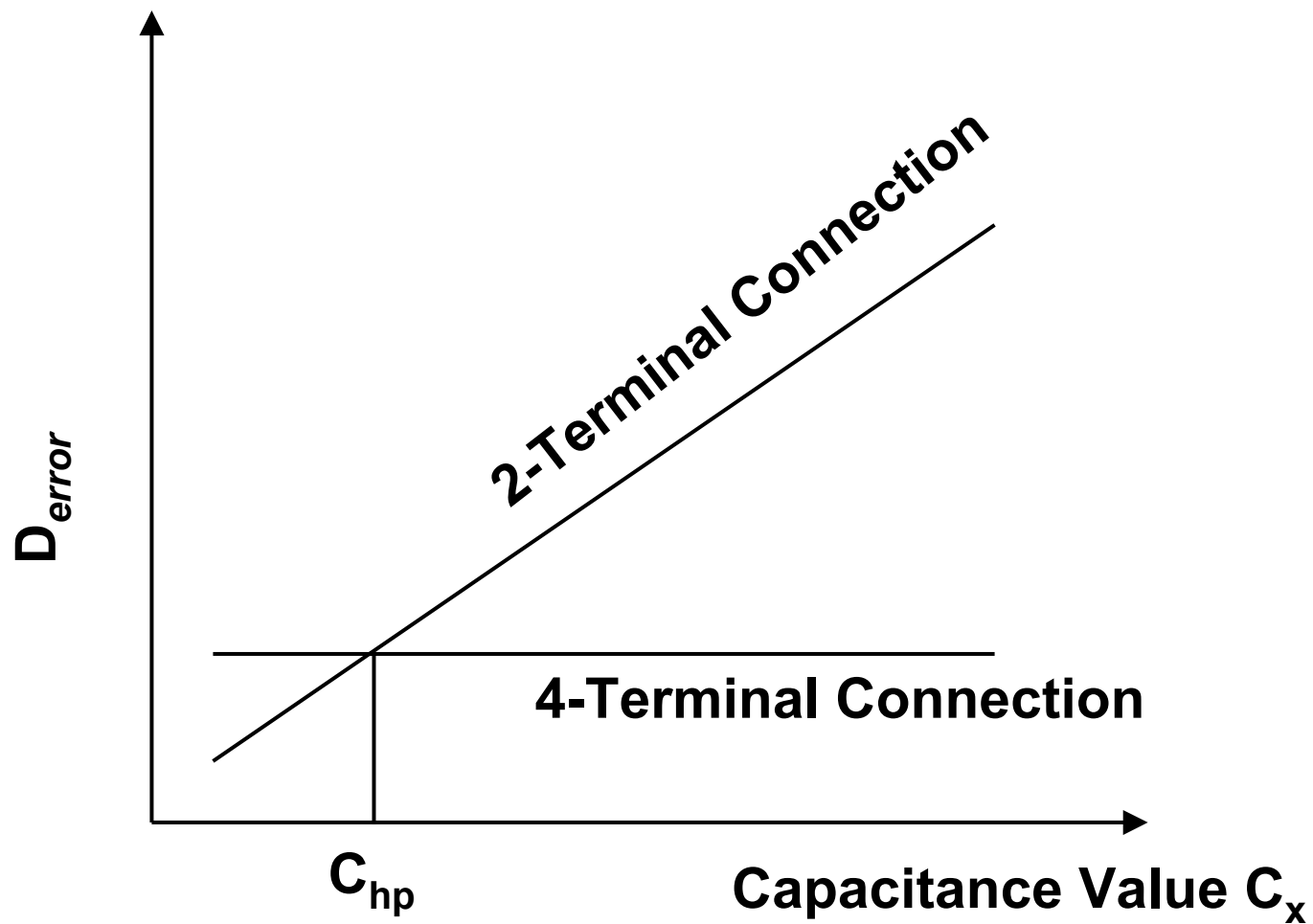
误差

- 接触电阻——4端(4T)连接

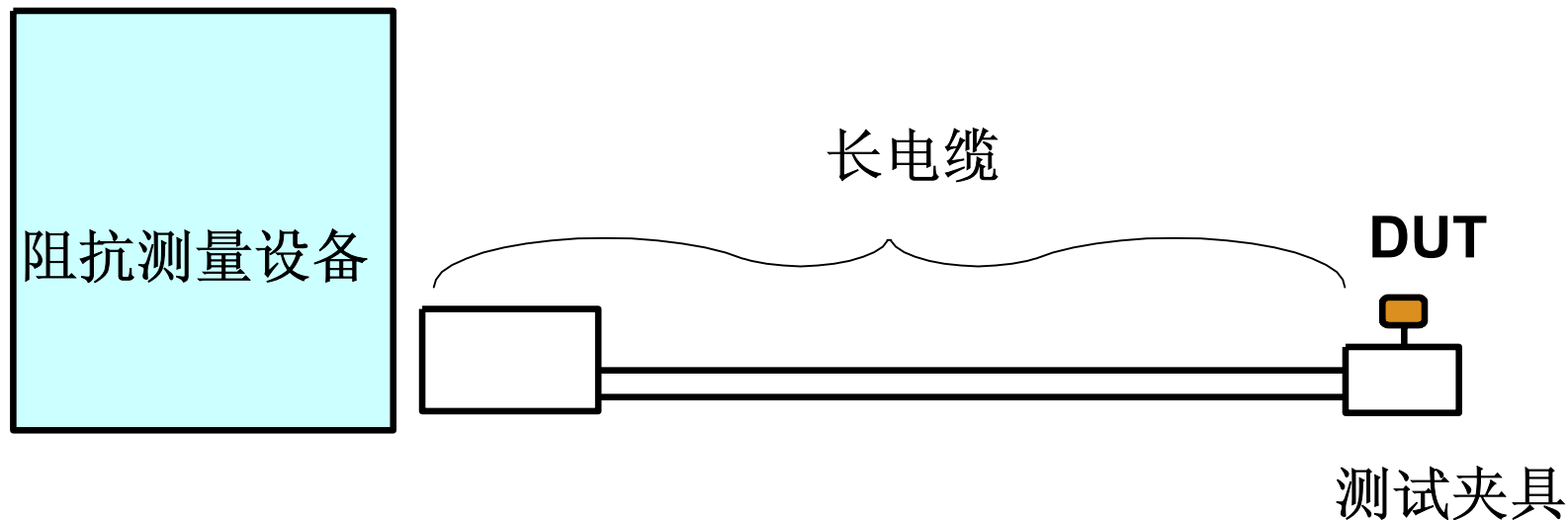


$$D_{erro} = -\omega(C_{hp}R_h + C_{lc}R_{lc})$$

2 端连接 vs.. 4 端连接的误差



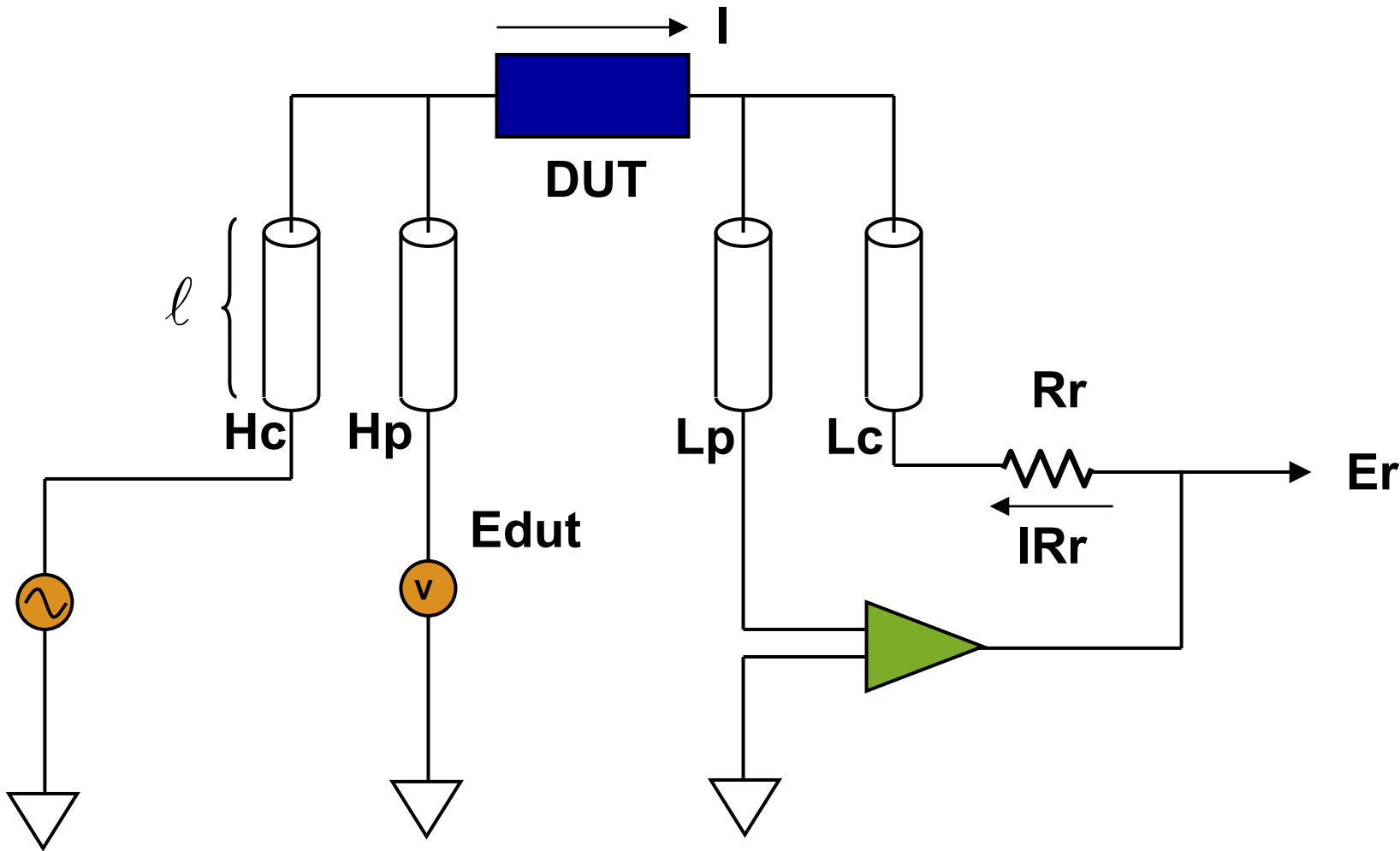
测试电缆延伸造成的误差



- 扩展电缆的影响：
 - 阻抗测量误差
 - 电桥不平衡

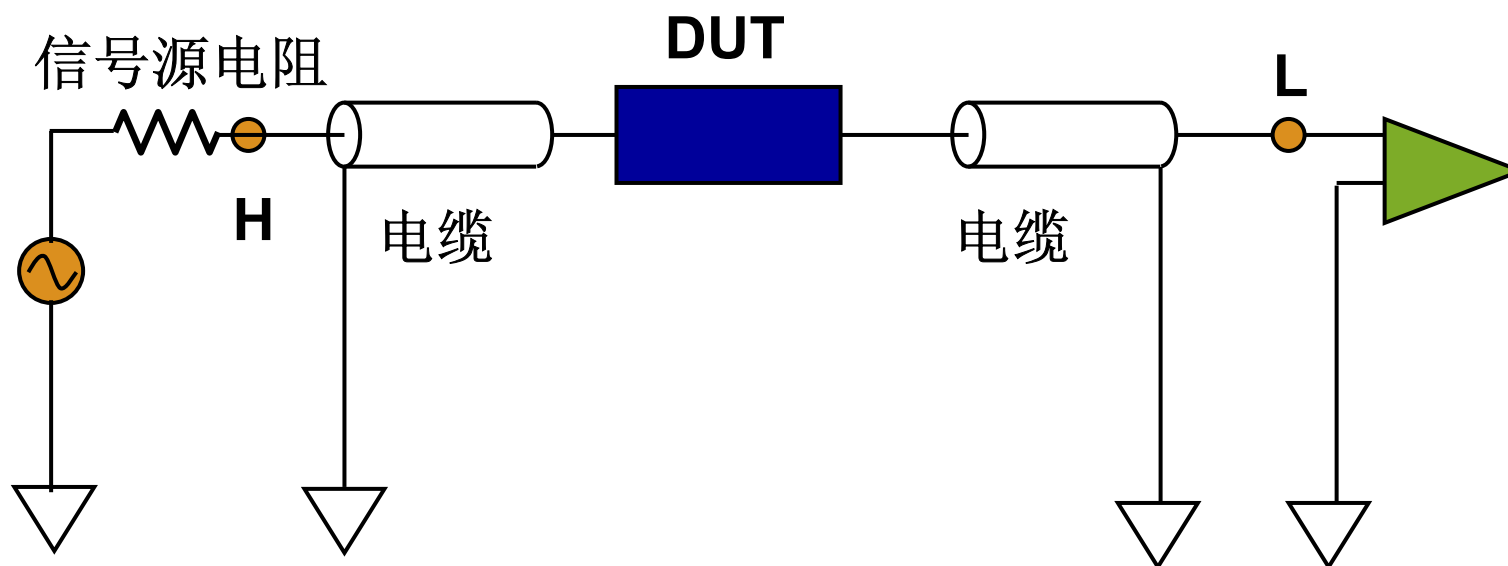


电缆长度补偿(高频)



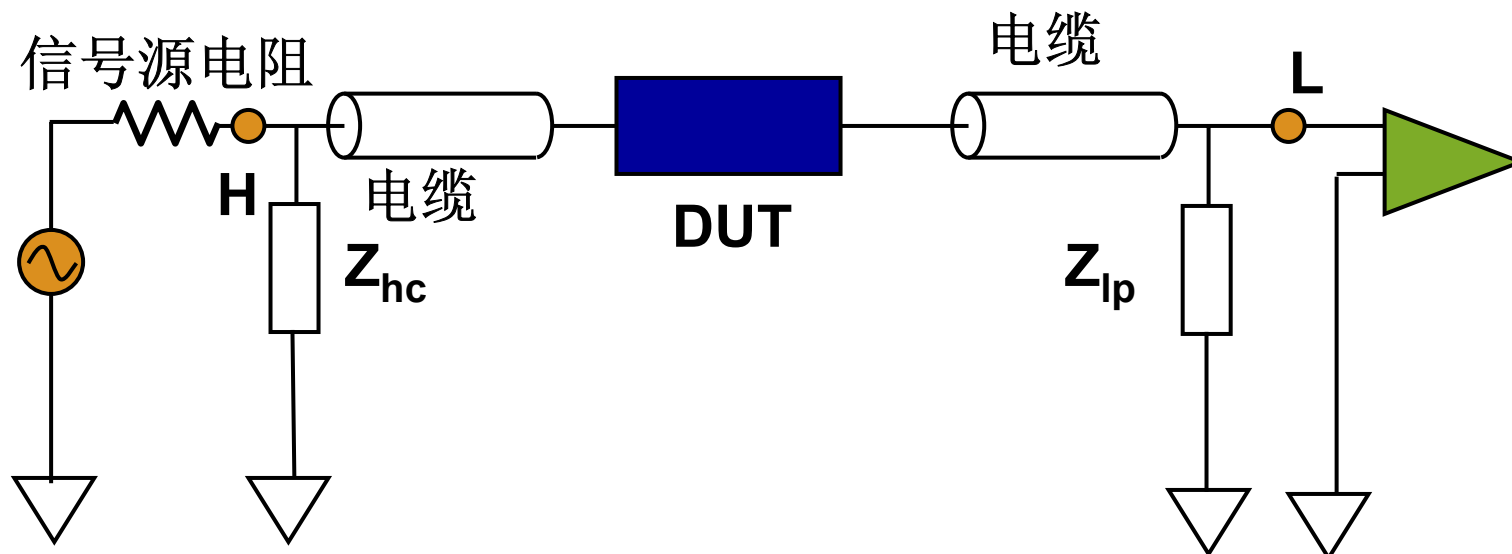
电缆长度补偿 (低频)

- 电缆连接在高端和低端



电缆长度补偿 (低频)

- 电缆延伸效应



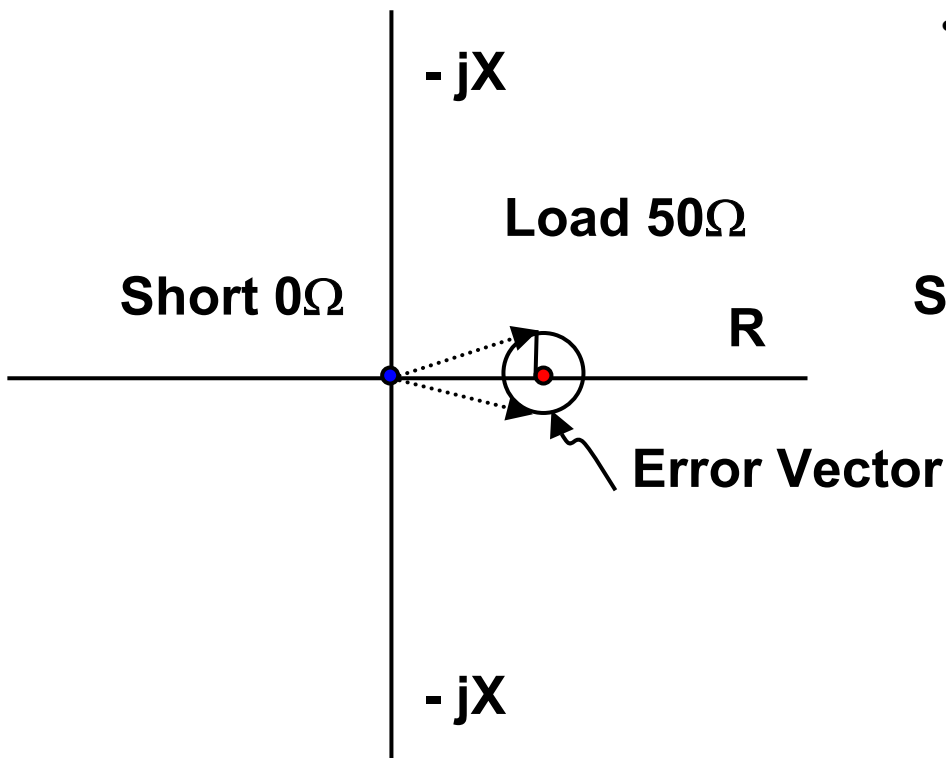
Z_{hc} : 由连接高端电缆的杂散电容产生的阻抗。这个阻抗降低测试信号和测试准确性。

Z_{lp} : 由连接低端电缆的杂散电容产生的阻抗。这个阻抗影响幅度测量并降低测量准确性。



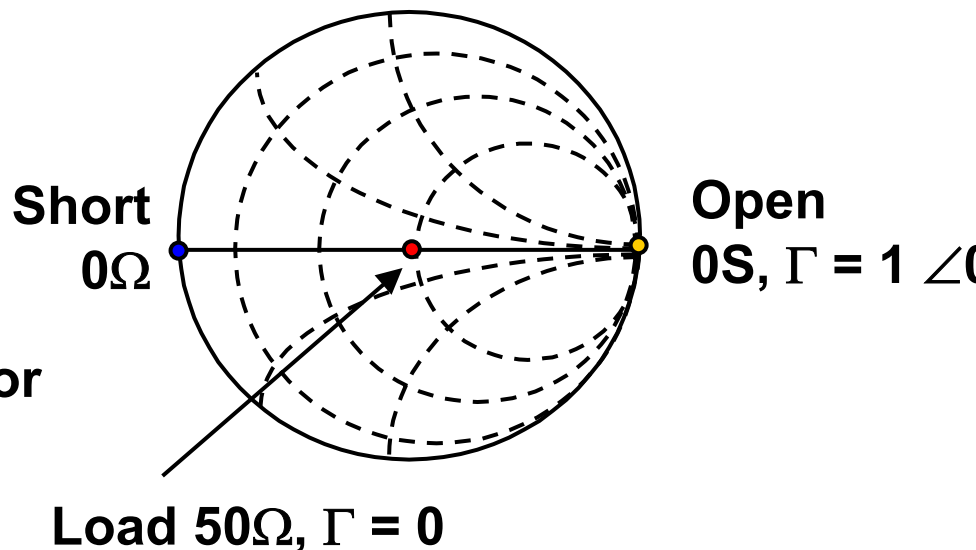
射频波段的补偿

- A. 矢量阻抗平面**



- B. 史密斯园图**

- 用来补偿的标准器件值

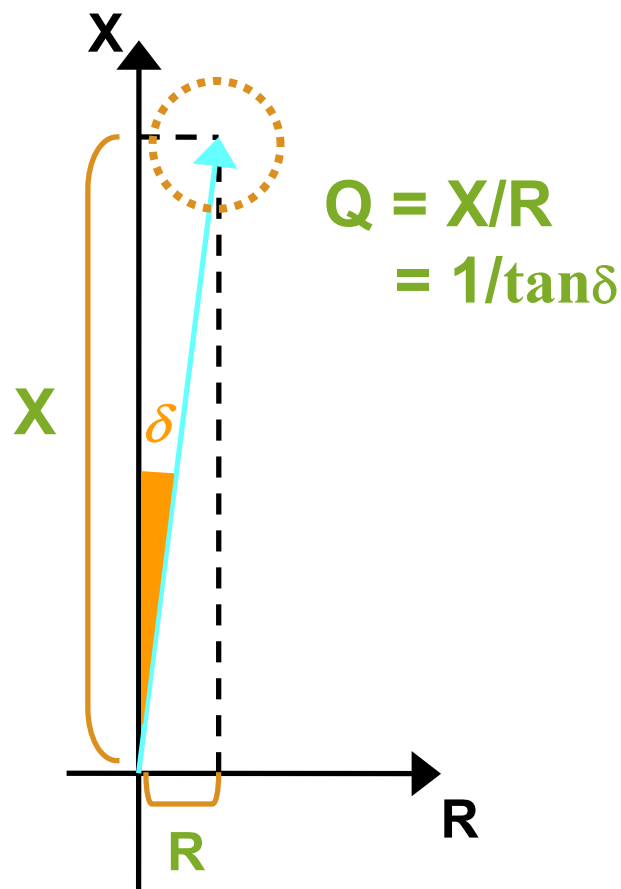


注意: 开路阻抗无限大, 因此无法在阻抗幅平面显示。



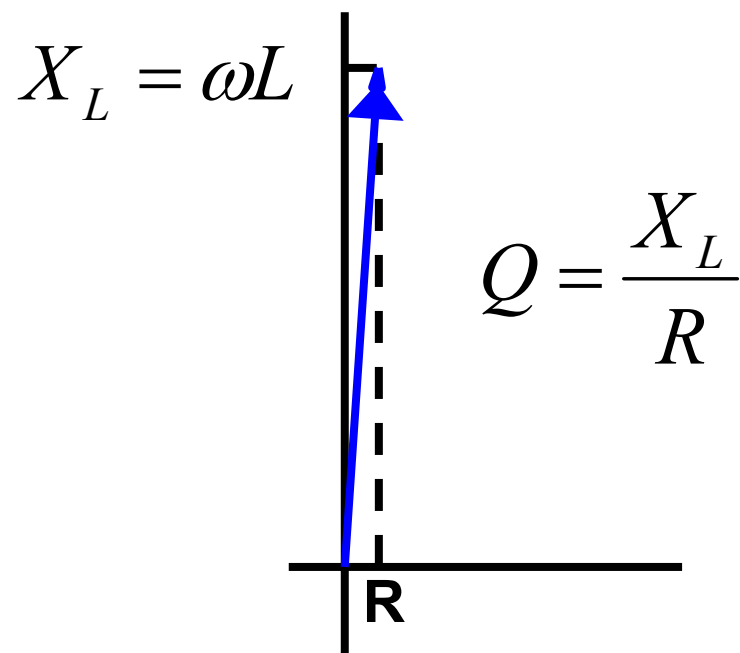
自动平衡电桥方法很难测高Q和低D

- **Q=100 (ESR is 1/100 of X)**
 - **0.5° δ change means 87% of R**

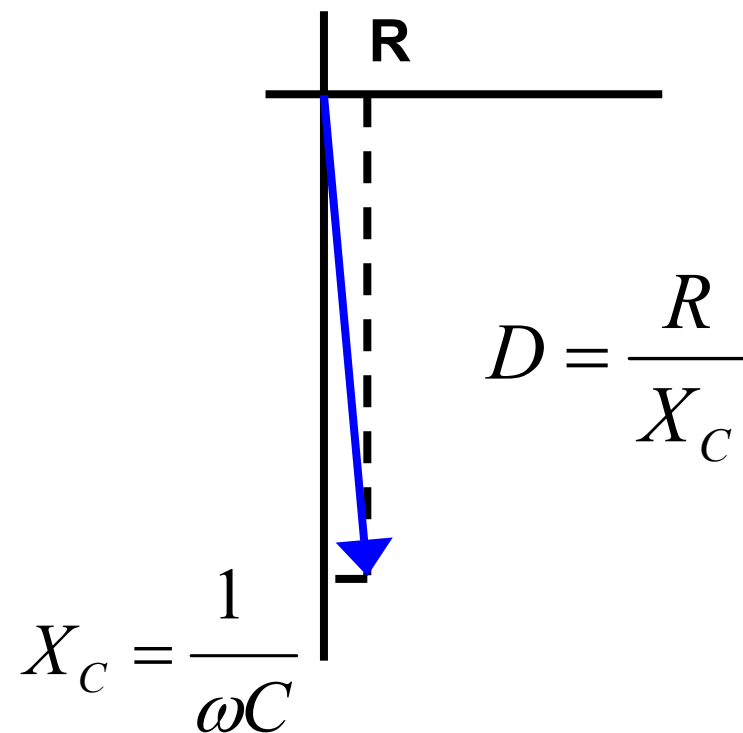


高 Q, 低 D 测量

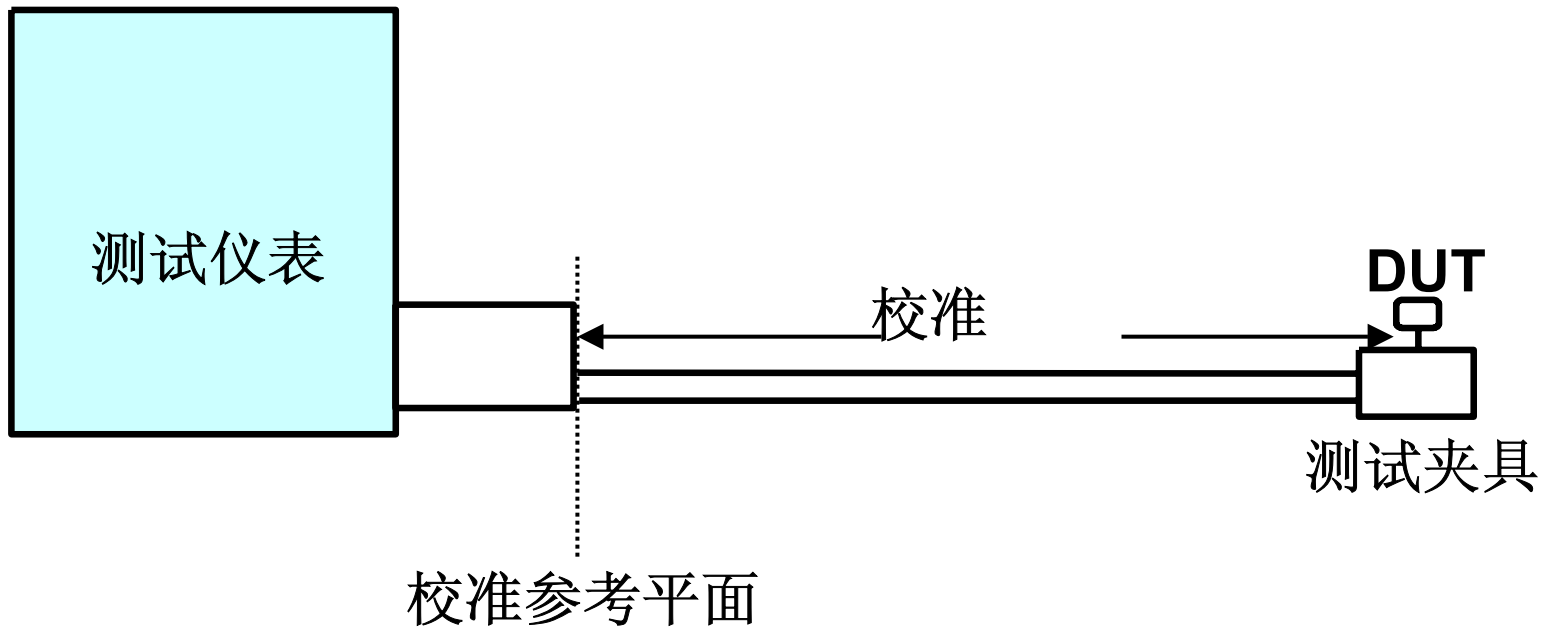
- 电感Q值测量



- 电容D值测量

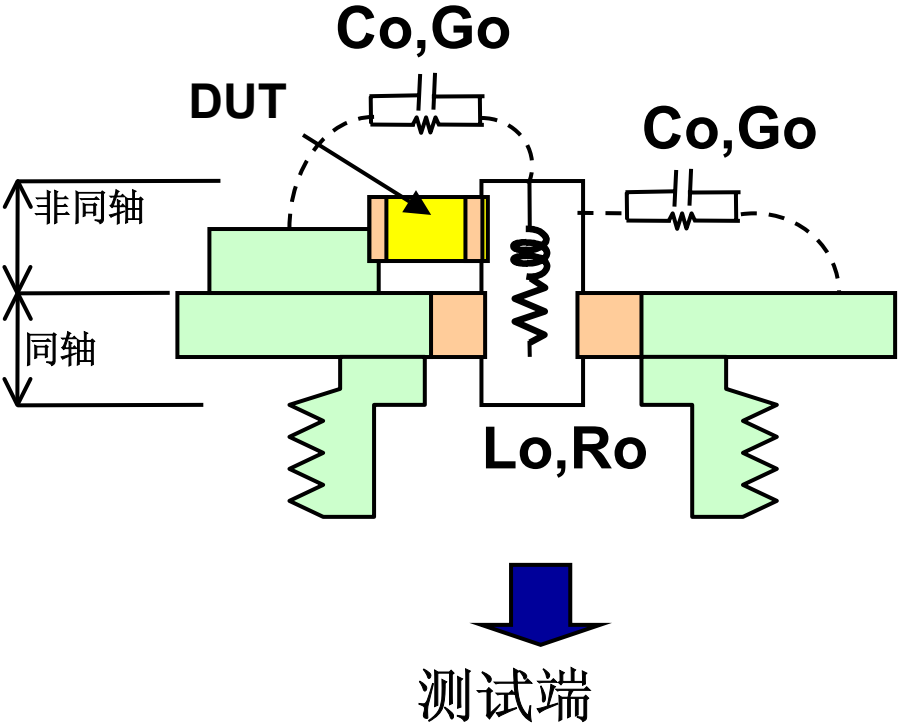


校准参考平面

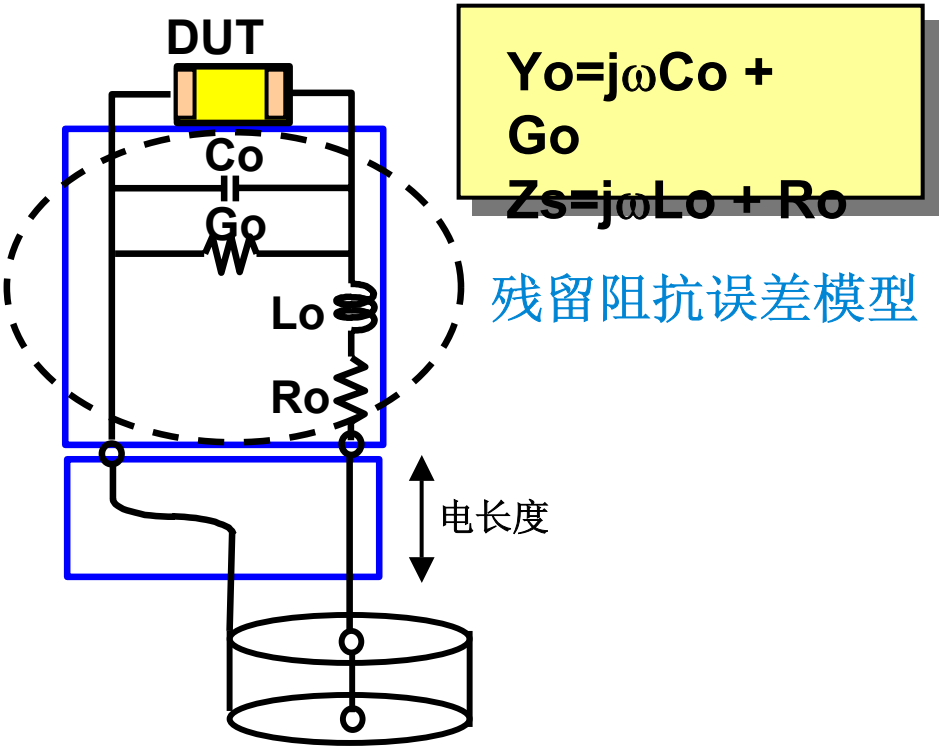


测试夹具误差模型

• A. 典型的测试夹具模型



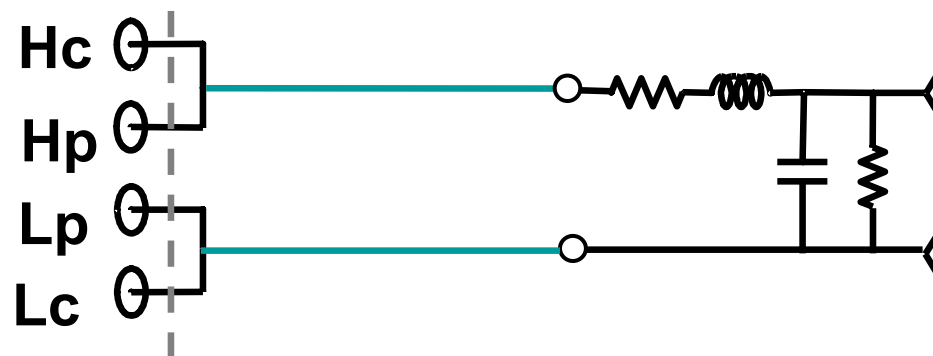
• B. 简单的等效误差电路模型



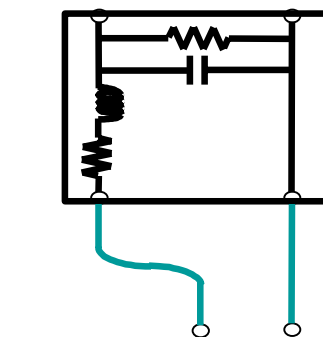
电长度补偿

- 自动平衡电桥技术
 - 电缆长度补偿
 - 采用负载补偿

- 射频 I-V 和反射系数技术
 - 端口延伸补偿
 - 采用复杂补偿



校准平面



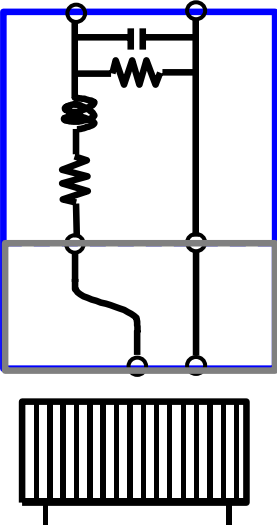
端口延伸

校准平面

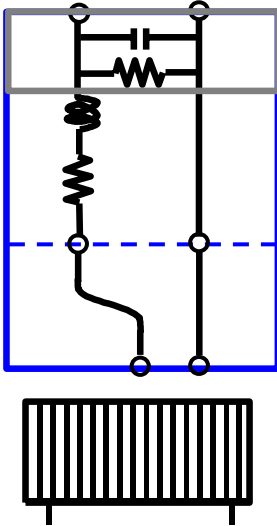


射频测试夹具补偿

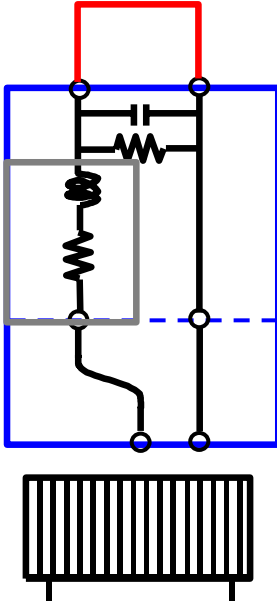
电长度



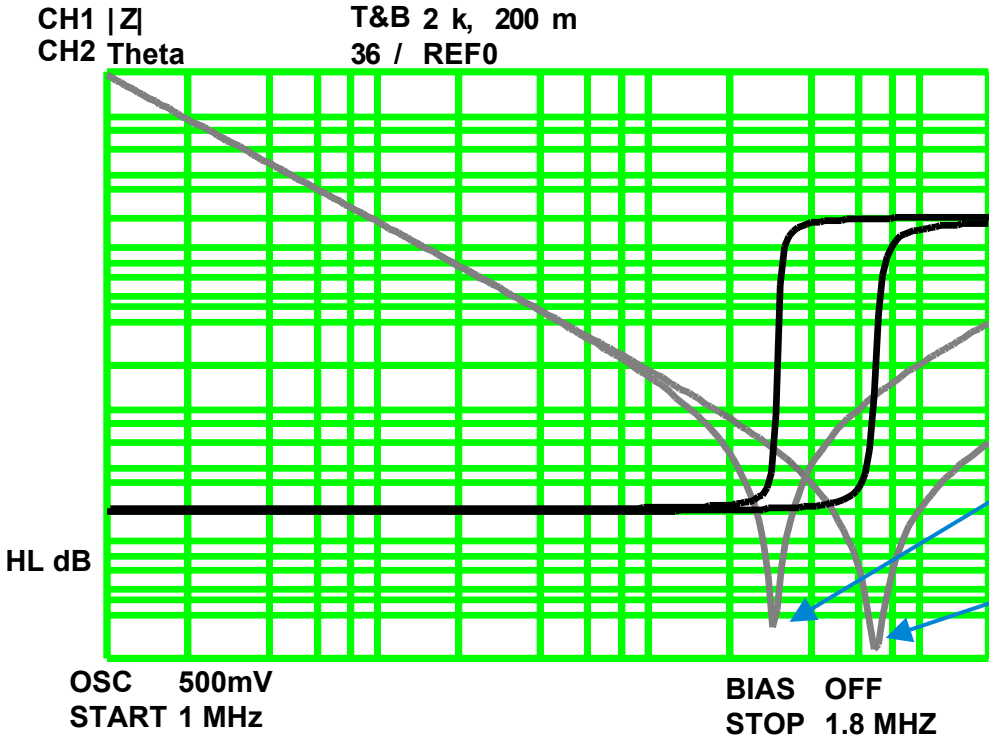
开路



短路



电长度补偿的结果



仅有延迟

延迟+OPEN/SHORT 补偿

为了更高的精度和可靠性 ...

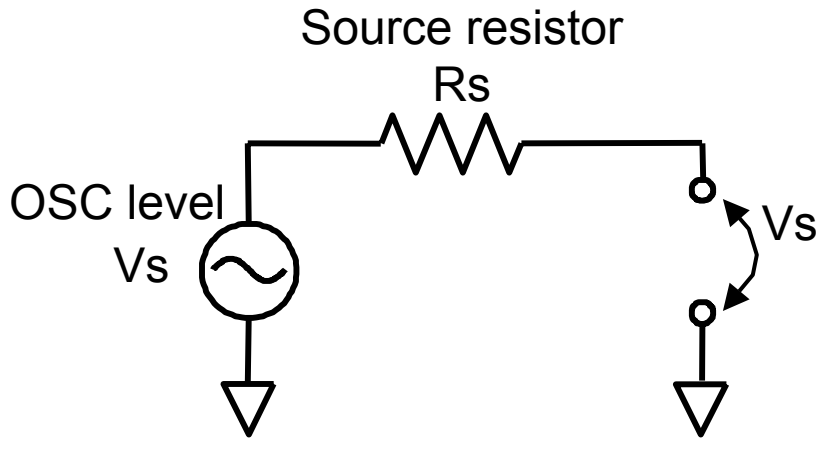
- 校准/补偿
 - 采用平均增加测量重复性
 - 为增大动态范围，信号电平应该尽可能大
 - **OPEN** 器件尺寸应该和**DUT**相同大小 (物理尺寸)
 - **SHORT** 器件尺寸应该和**DUT**相同大小 (物理尺寸)
- 测量 (校准/补偿后)
 - 保持测试温度稳定
 - **DUT**保持放置在相同位置
 - 校准后, 不要改变设置和电缆位置



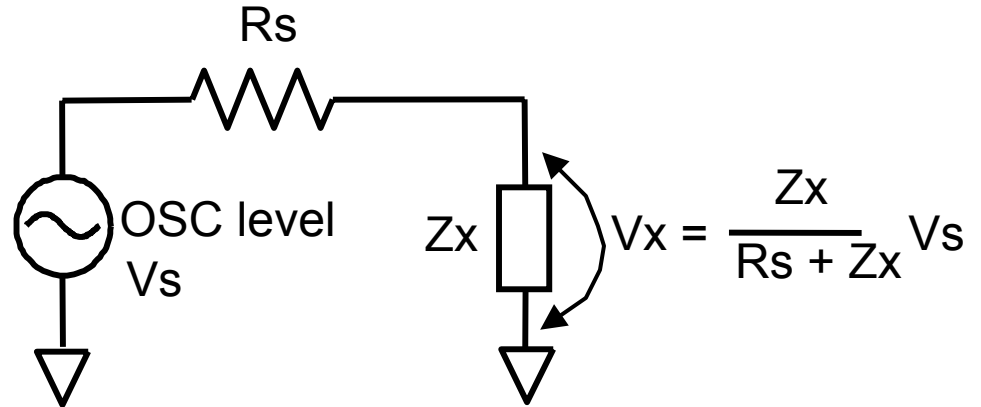
附录

关键测试功能

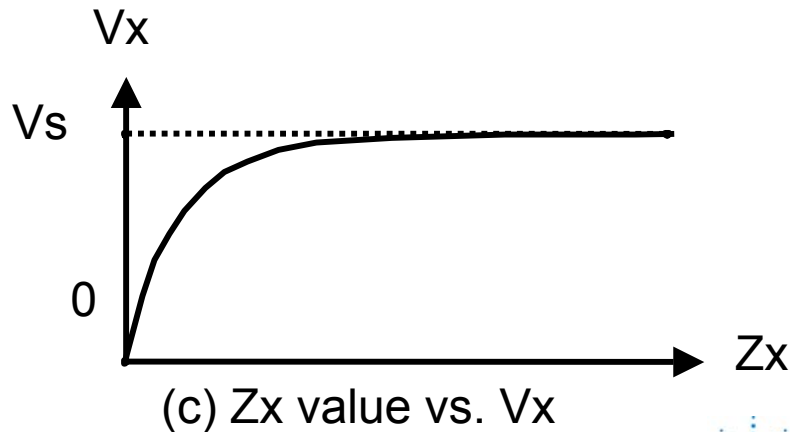
- (a) **OSC** 电平



(a) UNKNOWN terminal is open

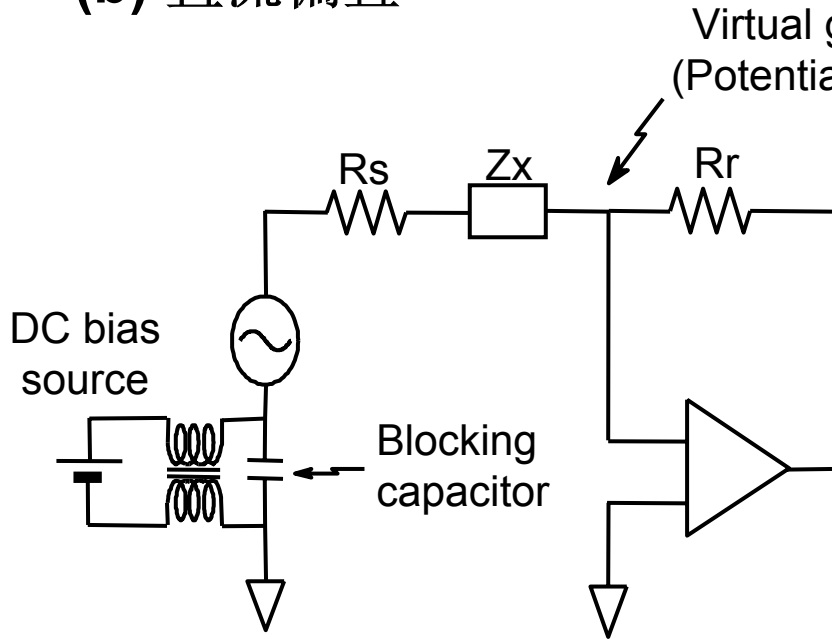


(b) DUT is connected to the UNKNOWN terminal

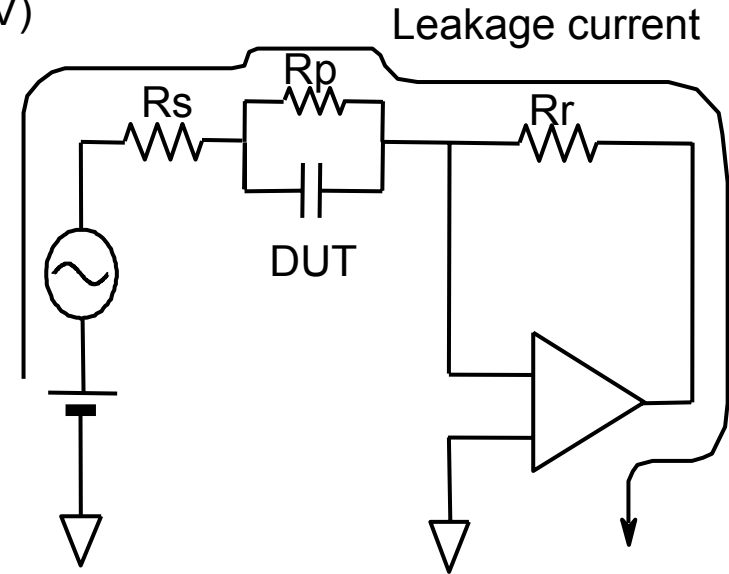


关键测试功能

- (b) 直流偏置



(a) Simplified diagram of DC bias measurement

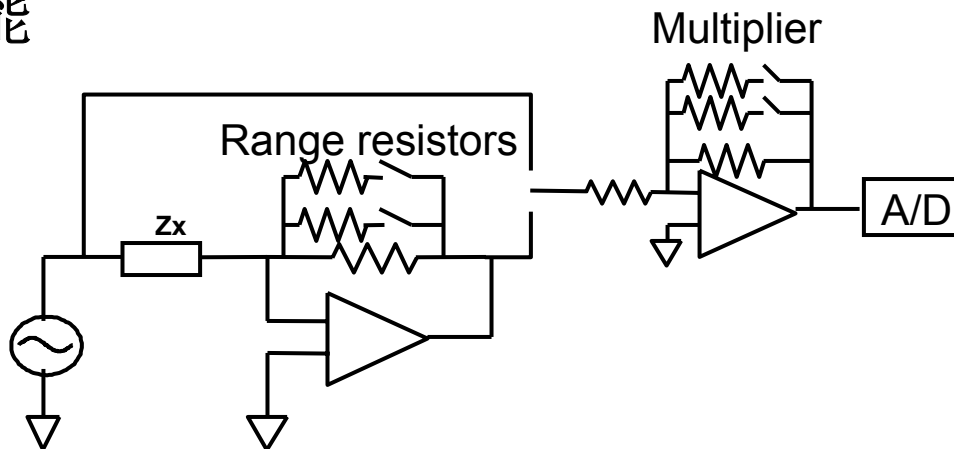


(b) When the DUT's R_p is low, leakage current decreases the DC voltage applied to the DUT.

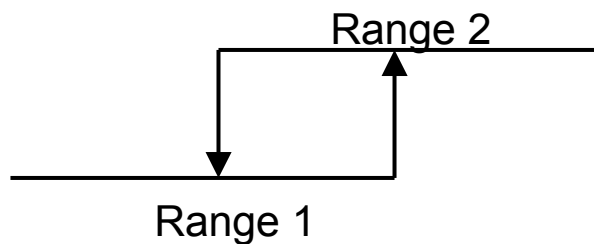


关键测试功能

- (c) 量程功能



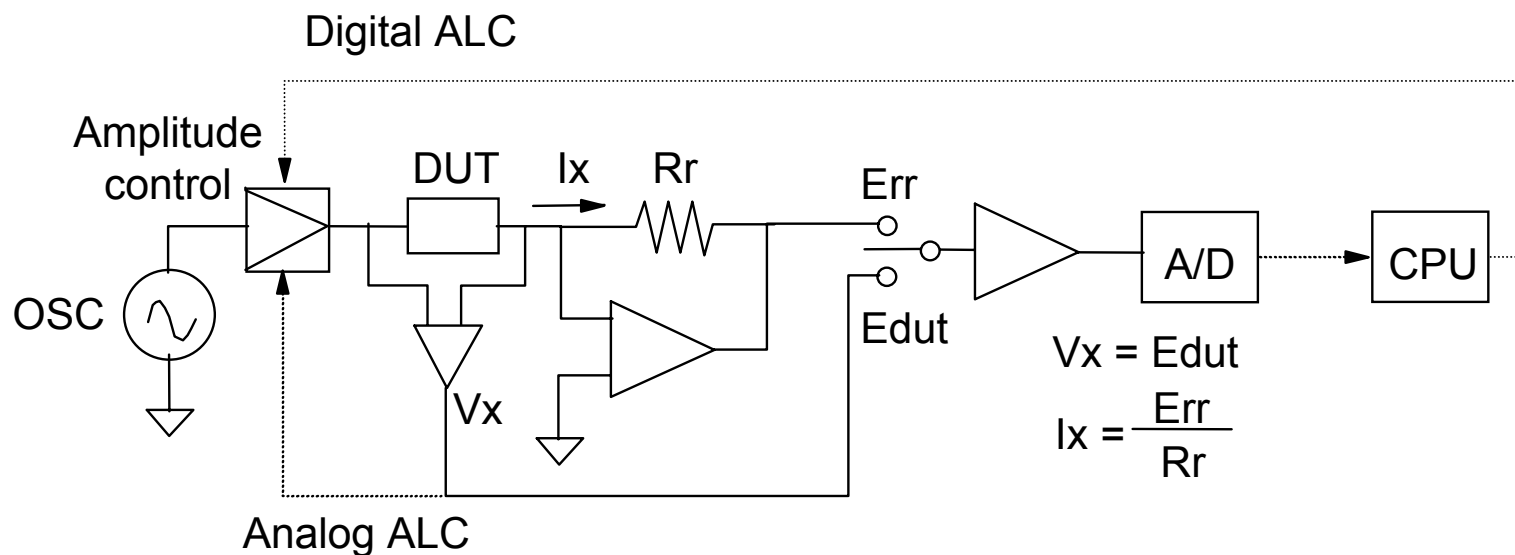
(a) Ranging is done by changing the range resistor and multiplier of the vector ratio detector.



(b) "Hysteresis" in the range boundary

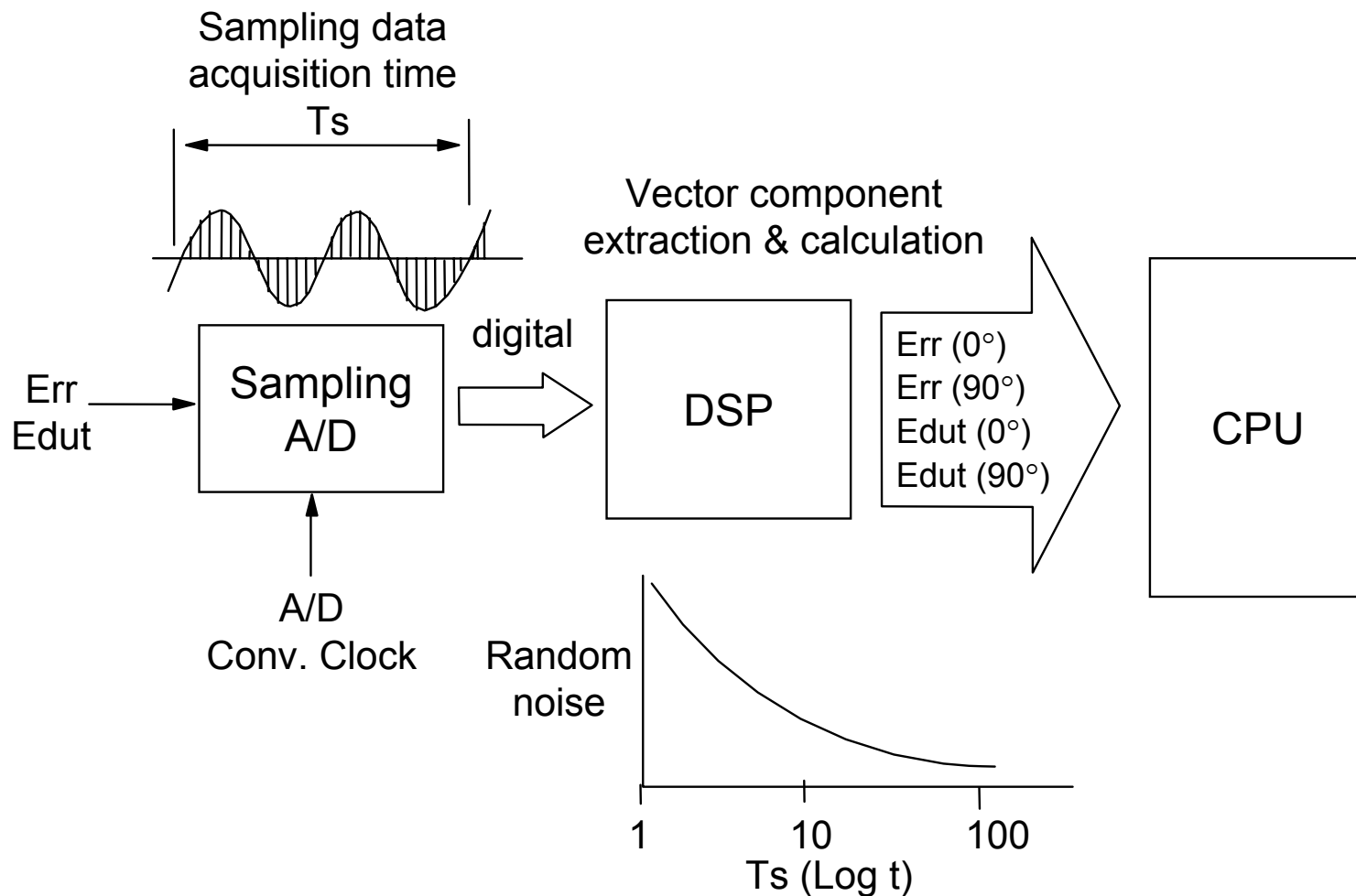
关键测试功能

- (d) 电平监测功能



关键测试功能

- (e) 测量时间和平均

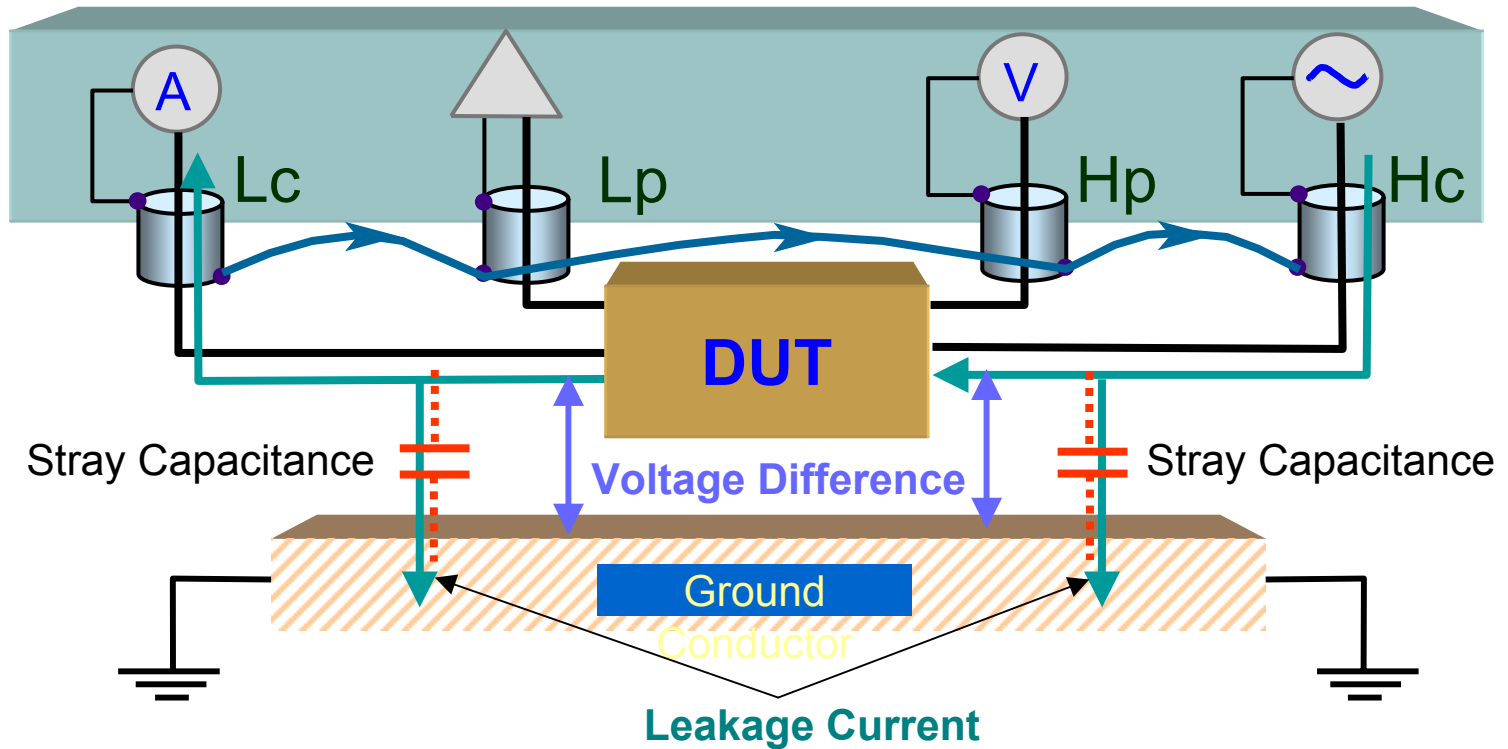


关键测试功能

- (f) 保护功能

Stray capacitance and leakage current

Auto-Balancing Bridge Type Instrument

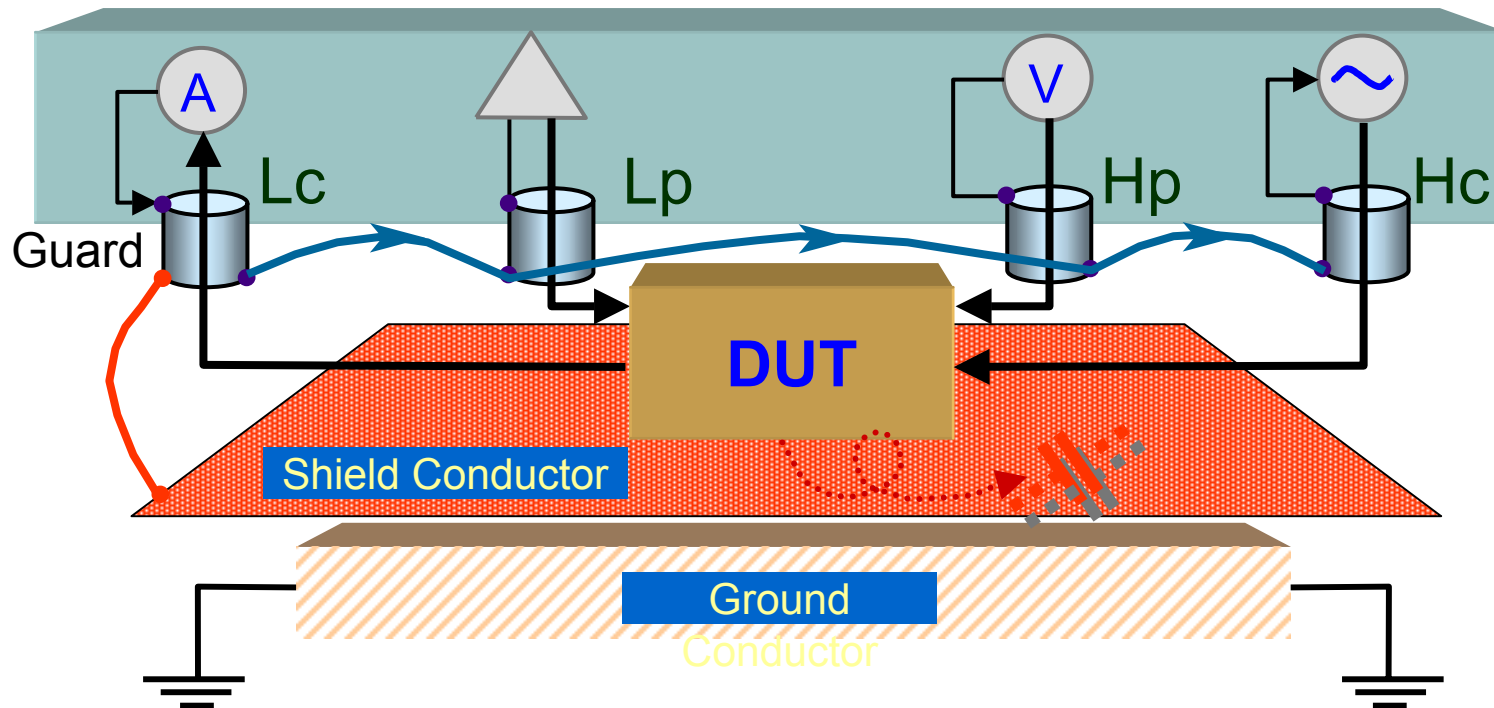


关键测试功能

- (f) 保护功能

Guard Mechanism and Solution

Auto-Balancing Bridge Type Instrument

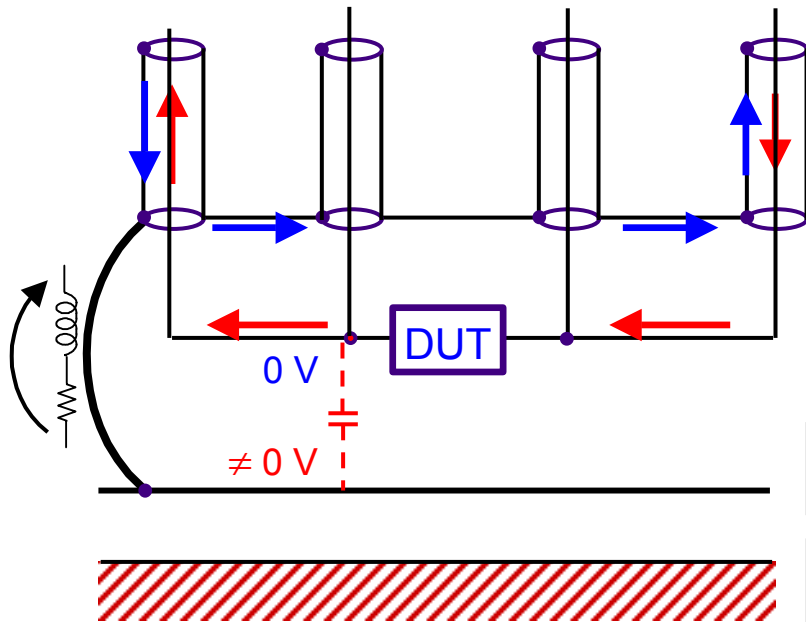


关键测试功能

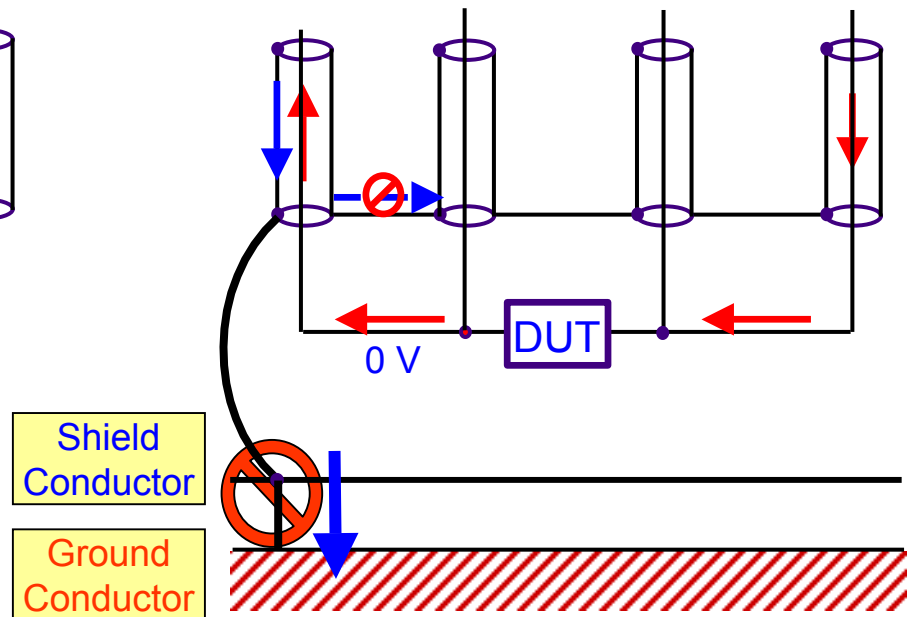
- (f) 保护功能

Key points to consider:

Minimize impedance of guard line.



Do NOT connect the guard terminal directly to the ground conductor.



Shield Conductor
Ground Conductor



资源与支持

- 主页：<http://www.agilent.com>
- 安捷伦向用户免费提供如下资源：
 - 最新仪表应用文章，可以通过连接进入阅览/下载。
 - 最新产品**Firmware**升级软件
 - 最新 **Plug&Play** 驱动软件
- 技术支持热线：**800-810-0189**
- 技术支持工程师：
胡海洋（021）64745500-8578

