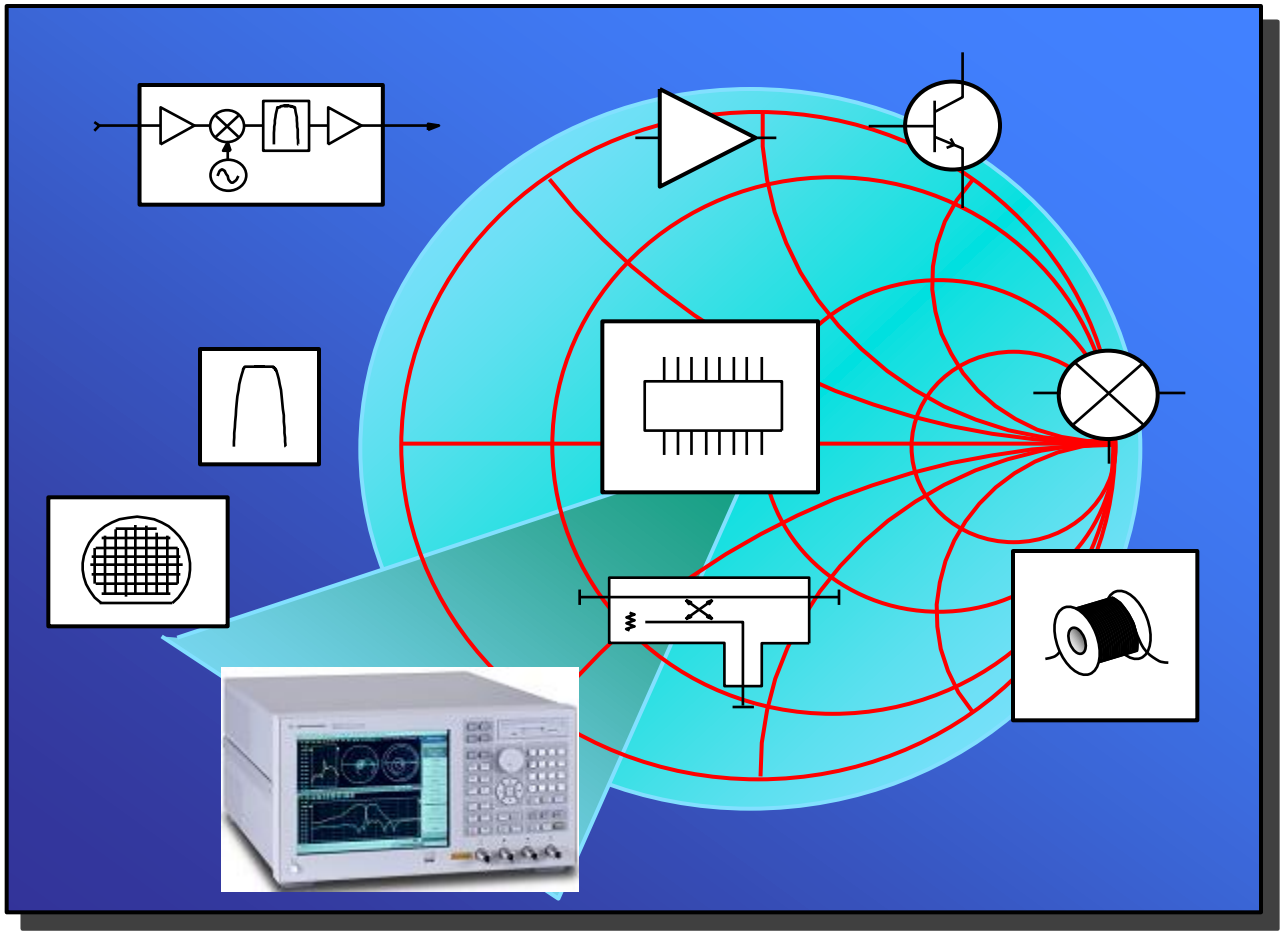
Agilent 系列
网络分析仪



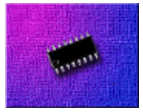
Agilent Technologies

网络分析仪

- 网络分析仪测试基本概念
- 网络分析仪 工作原理
- 误差和校准
- **ENA**
- **PNA**

系统组成及器件功能

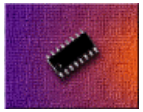
LNA



SAW 滤波器

平衡/非平衡转换

混频器

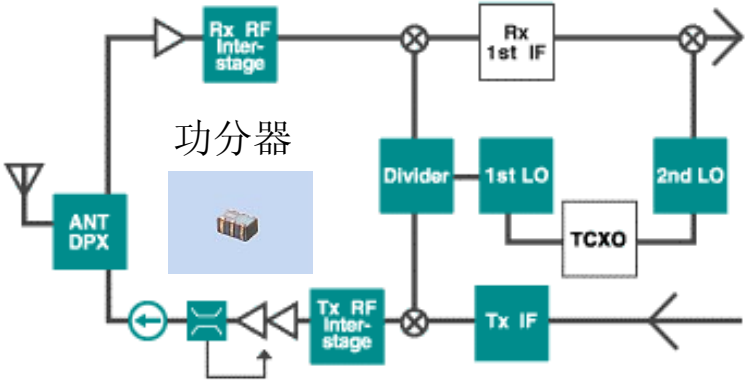


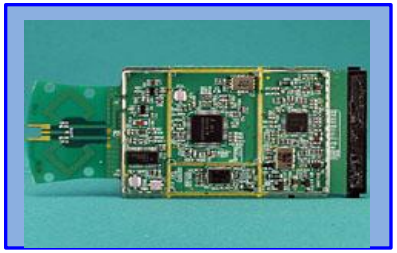
LO LC 滤波器

天线

双功器

射频前端模块



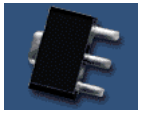


TX IF LC滤波器

隔离器

耦合器

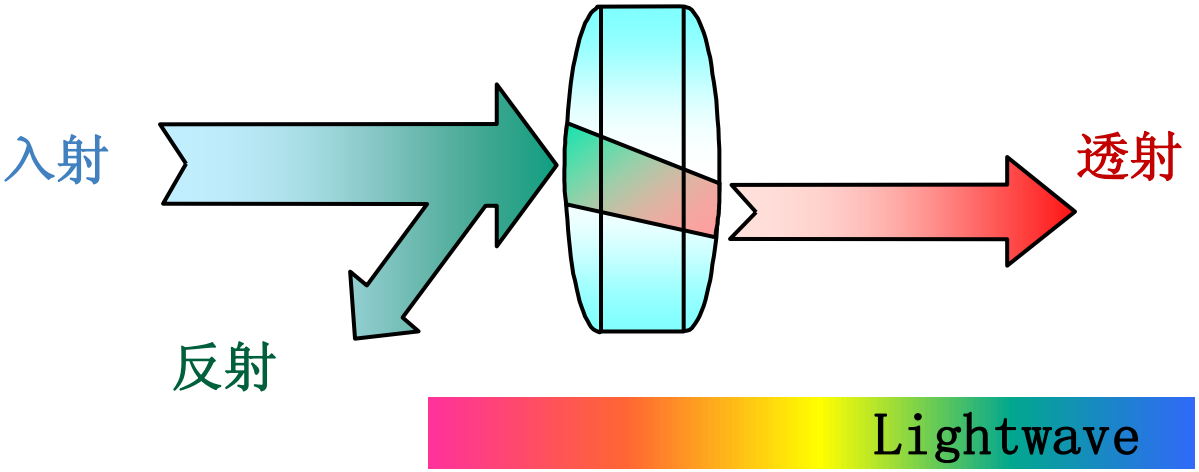
放大器



SAW 滤波器

平衡/非平衡转换

射频信号在器件中的传播

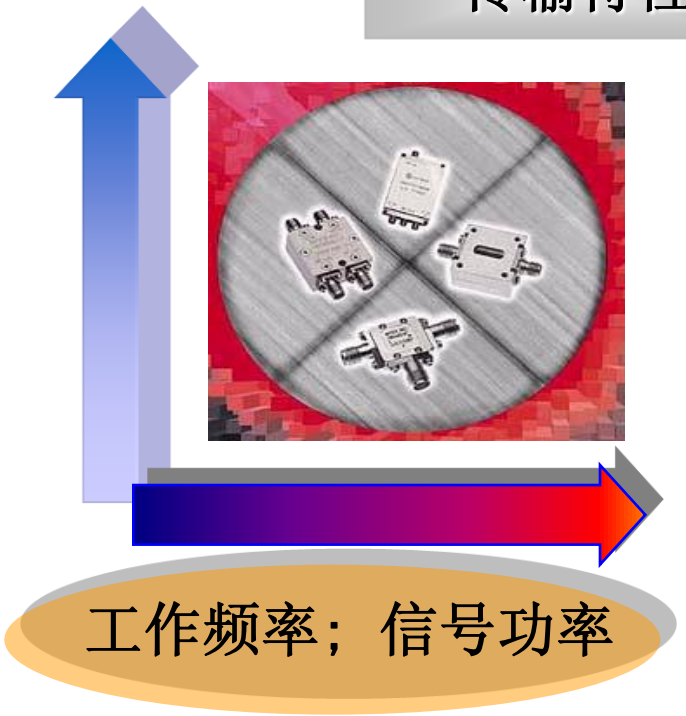


RF/MW

Agilent Technologies

网络分析仪测试要讨论的问题

- 器件性能的描述：传输特性；反射特性
- 器件传输特性/反射特性的指标定义？
  - Gain, Phase, Group delay
  - VSWR, Γ, ρ , Impedance
- 影响器件传输/反射特性的因素？
  - 工作频率
  - 信号功率
- 网络分析仪表显示结果



反射特性的参数定义：

反射系数
(电压比值)

$$\Gamma = \frac{V_{反射}}{V_{输入}} = \rho \angle \Phi = \frac{Z_L - Z_O}{Z_L + Z_O}$$

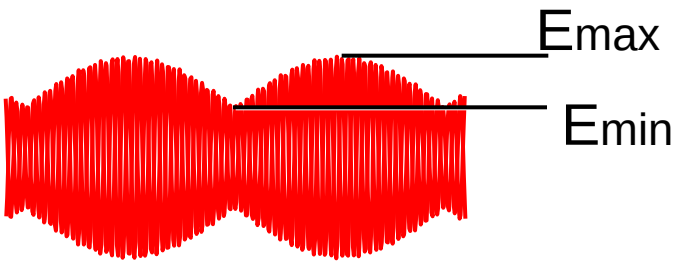
Z0 ： 传输线特性阻抗
Z1 ： 传输线终端负载

反射损耗
(功率比值)

$= -20 \log(\rho), \rho = |\Gamma|$

驻波比

Voltage Standing Wave Ratio



传输信号包络

$$VSWR = \frac{Emax}{Emin} = \frac{1+\rho}{1-\rho}$$

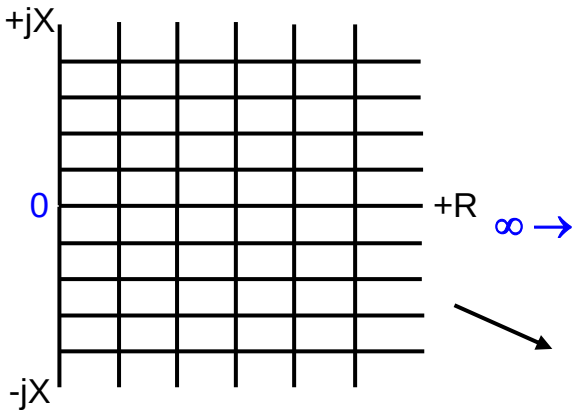
全匹配
($Z_L = Z_O$)

全反射
(Z_L = 开路, 短路)

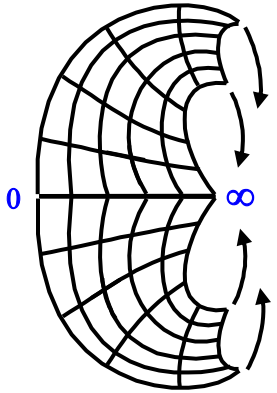
0	ρ	1
∞ dB	RL	0 dB
1	VSWR	∞

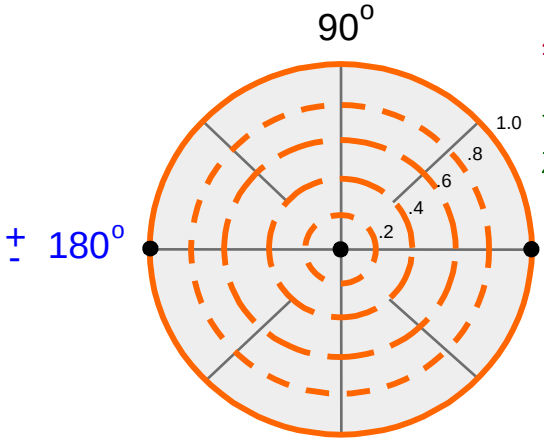
史密斯圆图 (Smith Chart)

对阻抗和反射的描述



Rectilinear impedance plane

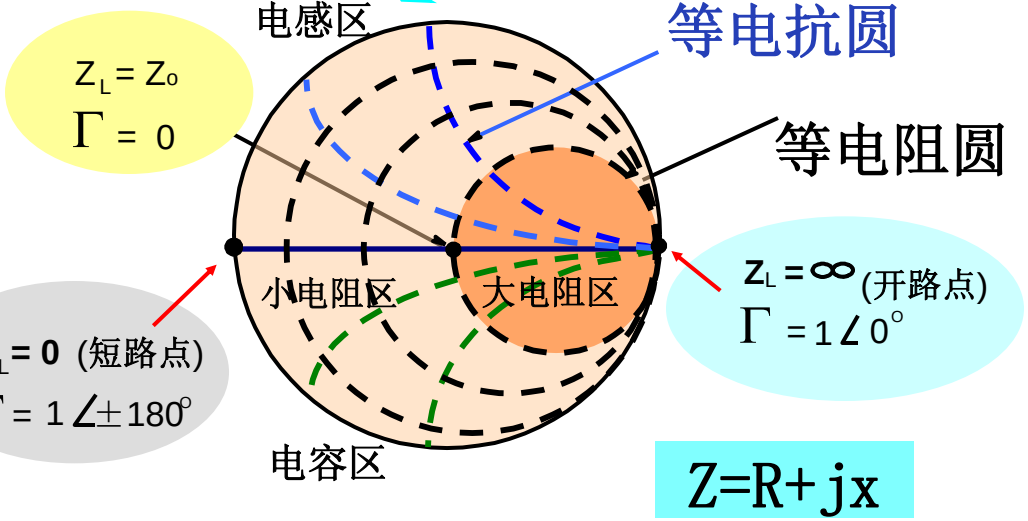




等反射系数圆

半径：反射大小

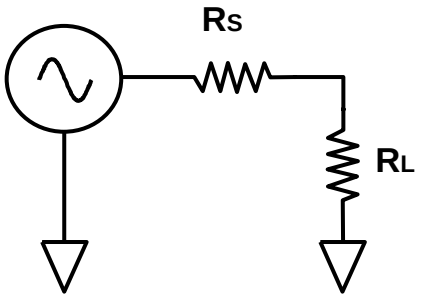
相角：反射相位



Smith Chart 圆图上一点位置反映对应的阻抗(R+jx)和反射(模和相位)

Z=R+jx

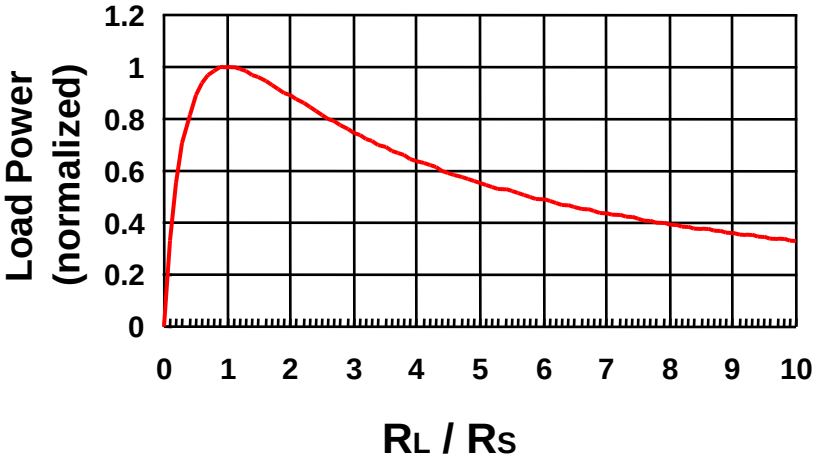
反射特性的说明

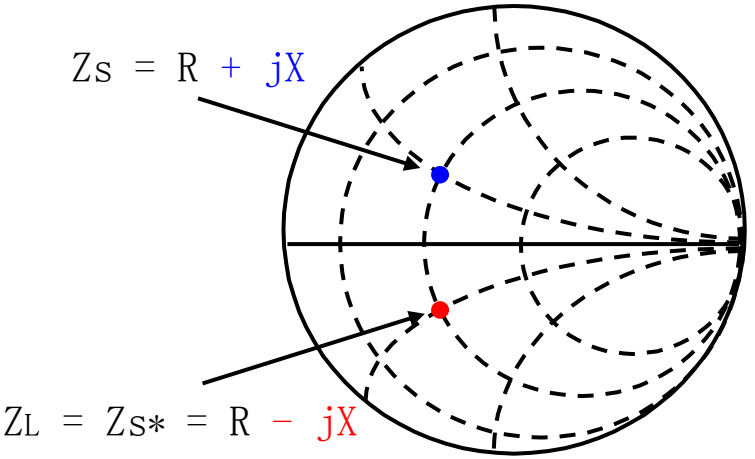


RL / Rs

对于复阻抗：功率最大传输效率条件：

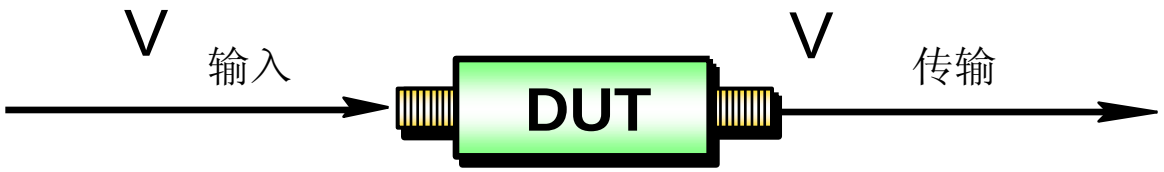
$Z_L = Z_S^*$（共轭匹配）





$R_L = R_S$：负载上最大功率传输

传输特性

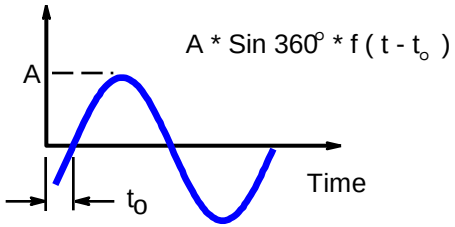


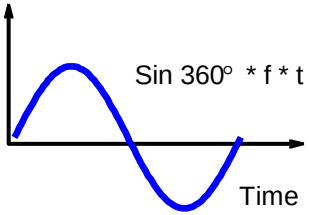
传输系数 = $T = \dfrac{V_{Transmitted}}{V_{Incident}} = \tau\angle\phi$

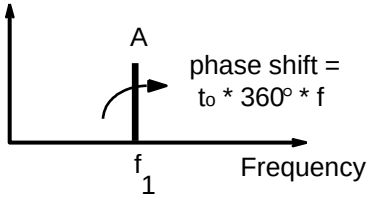
插入损耗 (dB) = - 20 Log $\left| \dfrac{V_{Trans}}{V_{Inc}} \right|$ = - 20 log τ

增益 (dB) = 20 Log $\left| \dfrac{V_{Trans}}{V_{Inc}} \right|$ = 20 log τ

线性器件与非线性器件

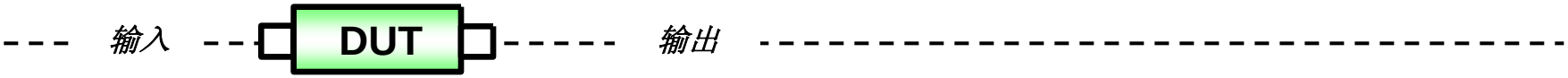


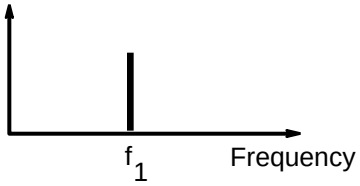


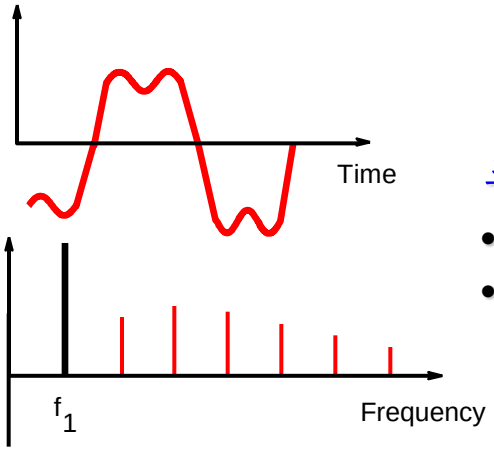


线性特性：

- 输入信号与输出信号同频率
- 输出信号幅度和相位会发生变化







非线性特性：

- 输入/输出信号不同频率
- 产生新的频率成份

满足波形不失真线性系统的条件

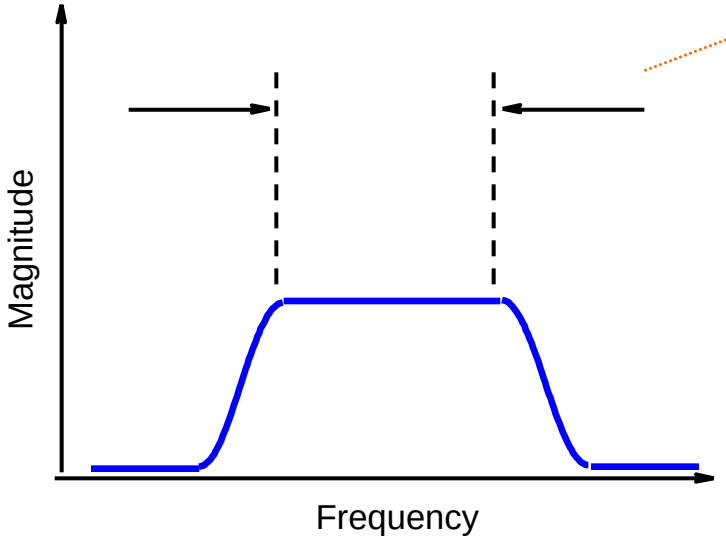
$V_{输入} = f(t)$

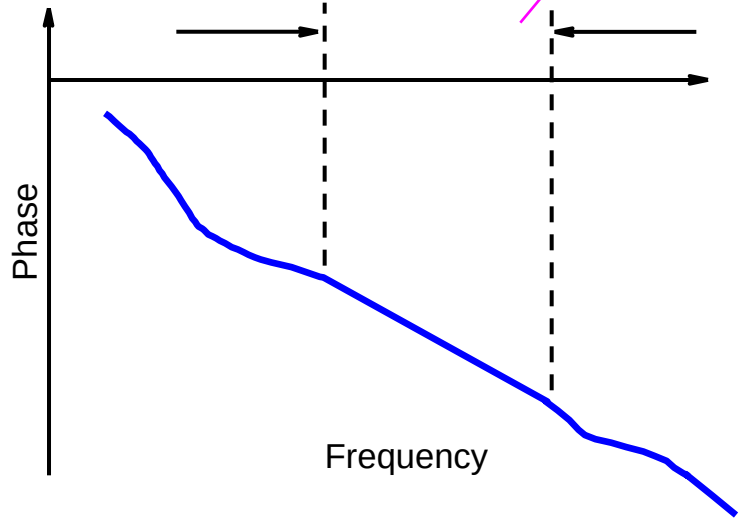
DUT

$V_{输出} = a\,f(t - to)$

系统频率带宽内幅频特性为常量

系统频率带宽内相频特性为线性





幅度/频率特性要求

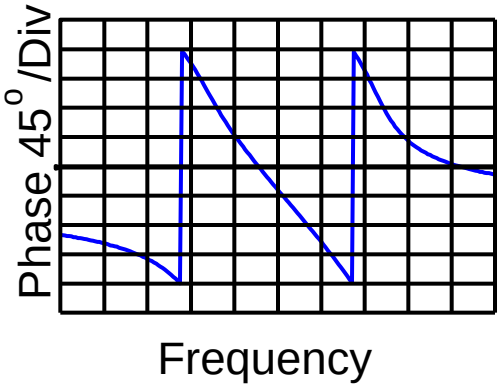
相位/频率特性要求

对系统相位特性的描述

网络分析仪的相位补偿处理功能：

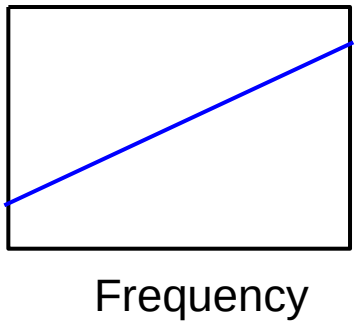
- **电延迟功能(Electrical delay）:**通过时间补偿消除被测件相频特性中线性部分
- **相位偏移（Phase offset):** 被测件相位特性中加入固定偏置
- **端口延伸（Port Extension)：** 测试仪表端口电延时补偿

器件相频特性

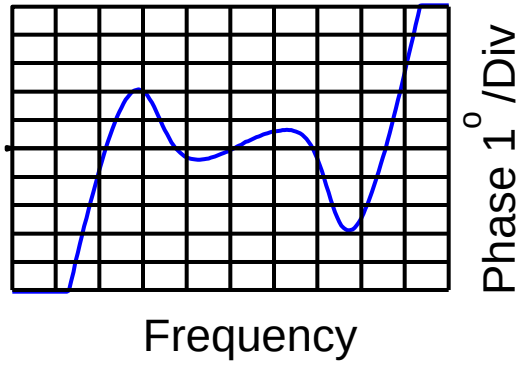


网络分析仪相位补偿

(Electrical delay)



器件相位非线性



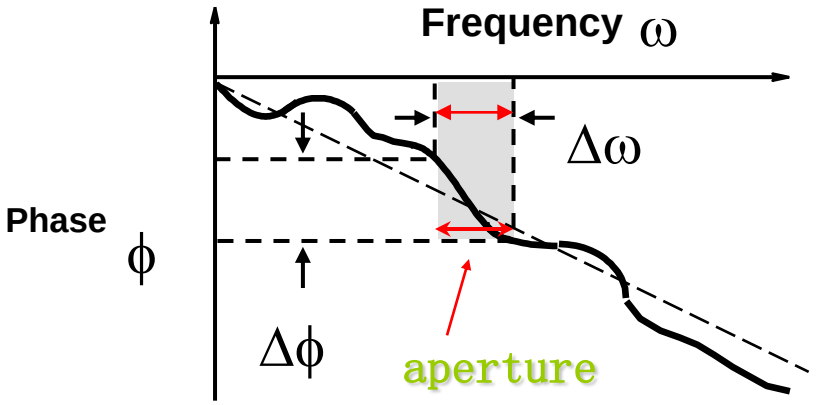
应用：

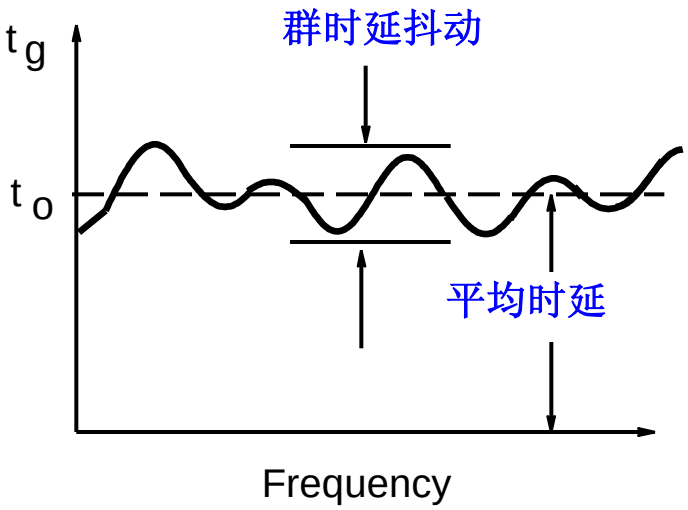
测量器件相位特性
难于定量分析相位特性线性

应用：

便于对相位特性线性的分析

群时延Group Delay (GD)





Group Delay (t_g) =

$$\frac{-d\phi}{d\omega} = \frac{-1}{360^o} * \frac{d\phi}{df}$$

ϕ in radians

ω in radians/sec

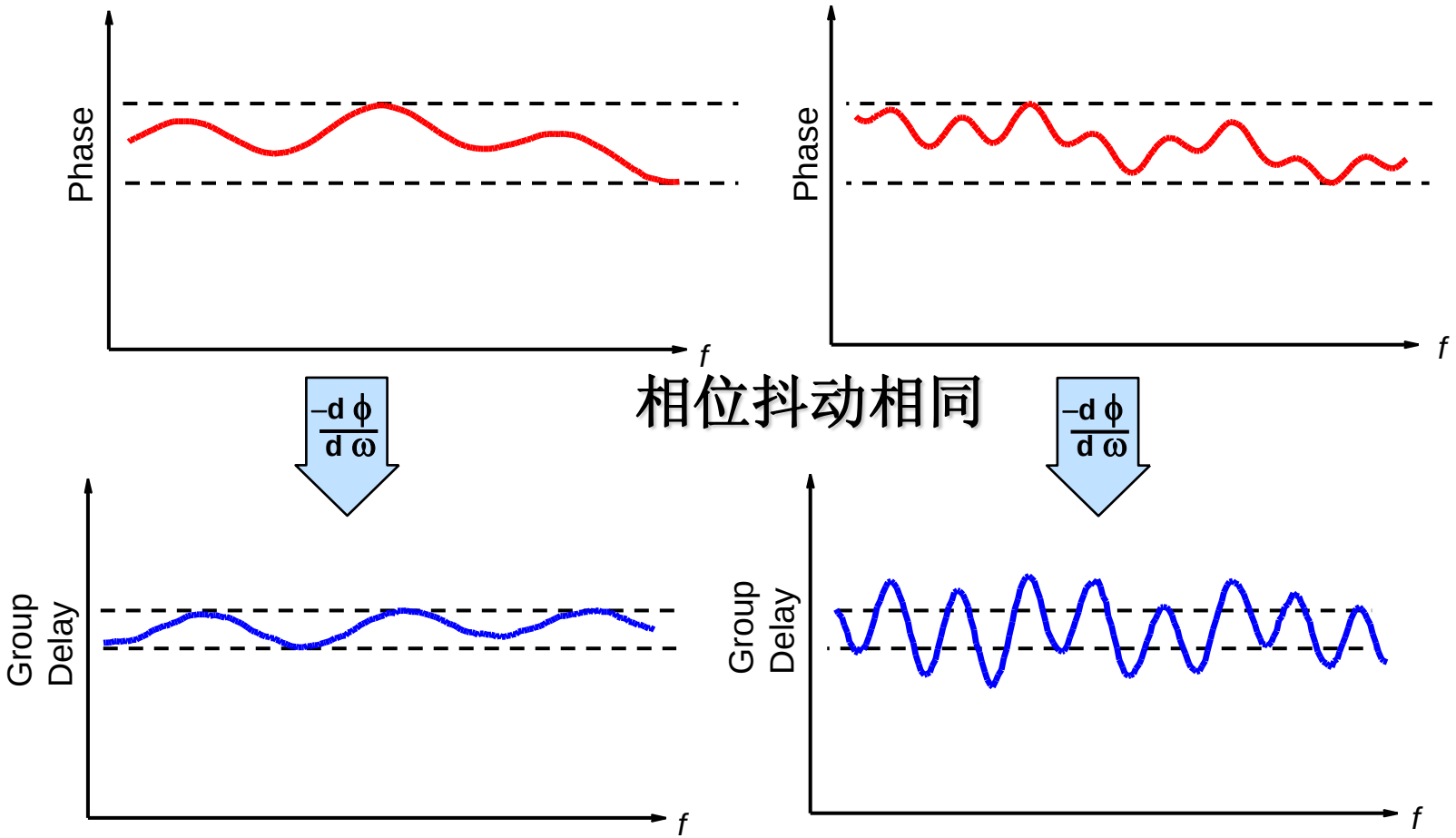
ϕ in degrees

f in Hertz ($\omega = 2\pi f$)

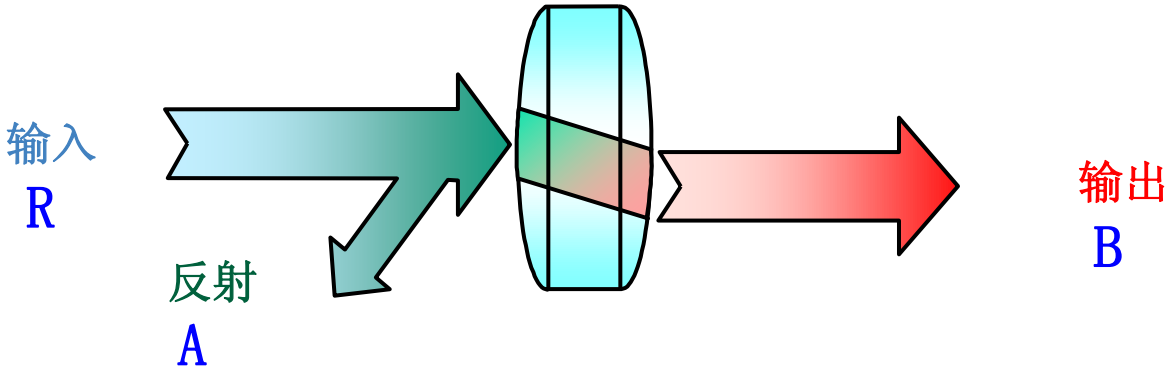
网络分析仪通过测试相/频特性得到器件延迟性能

- GD 抖动反映器件相位特性线性
- GD平均值反映器件的平均时延

通过群时延指标反映器件相位线性



完整的器件指标描述



反射特性

$$\frac{\text{Reflected}}{\text{Incident}} = \frac{A}{R}$$

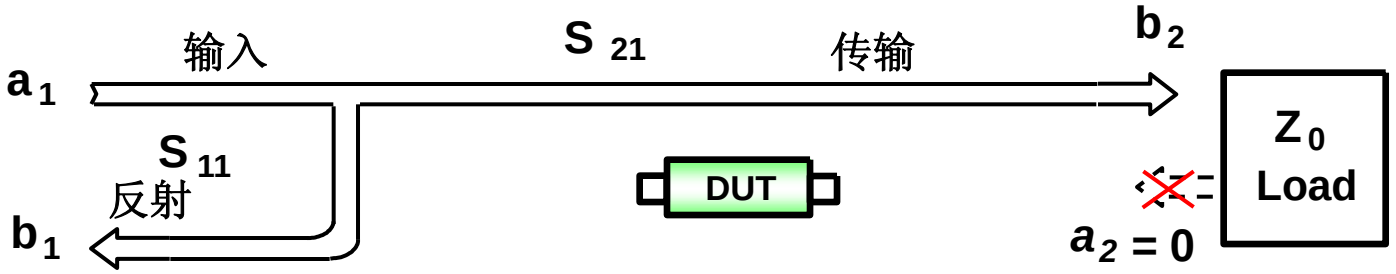
- SWR
- S参数 S11,S22
- 反射系数 Γ, ρ
- 阻抗 R+jX, G+jB
- 反射损耗

传输特性

$$\frac{\text{Transmitted}}{\text{Incident}} = \frac{B}{R}$$

- 增益
- S参数 S21,S12
- 传输系数 T,τ
- 相位 Phase
- 群延时 Delay

S参数的定义



$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_1}{a_1}\Big|_{a_2=0}$$

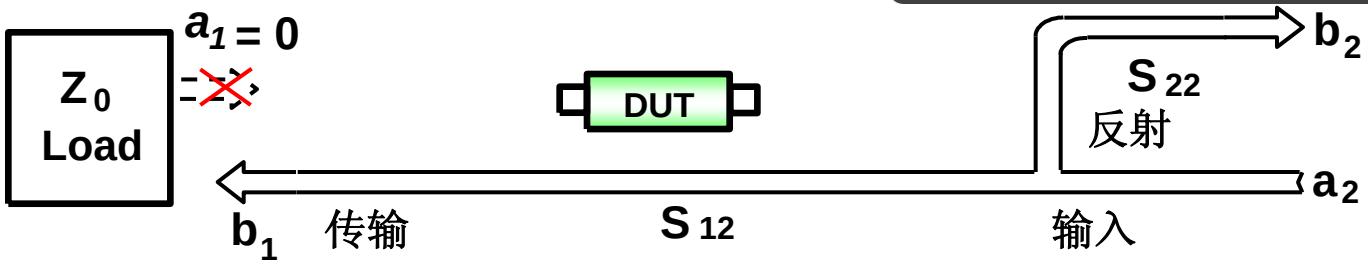
$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_2}{a_1}\Big|_{a_2=0}$$

S-parameters

电压线性值定义

$$S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_2}{a_2}\Big|_{a_1=0}$$

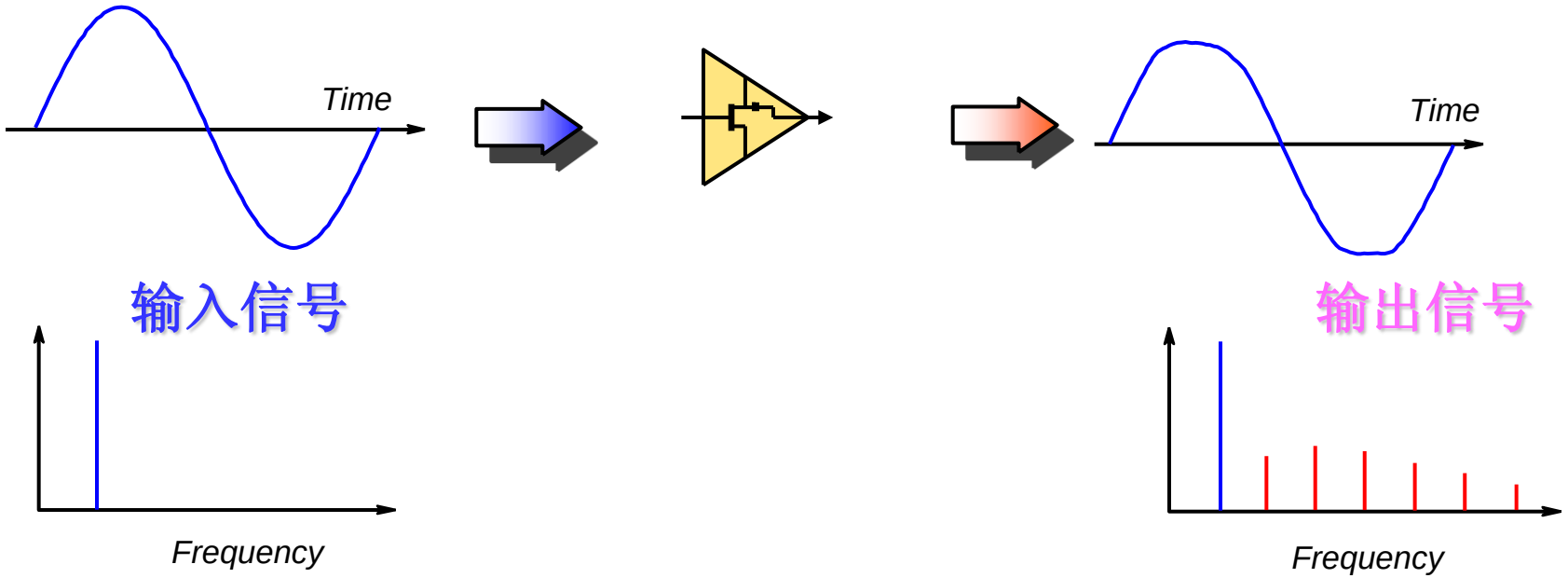
$$S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_1}{a_2}\Big|_{a_1=0}$$



器件的非线性失真

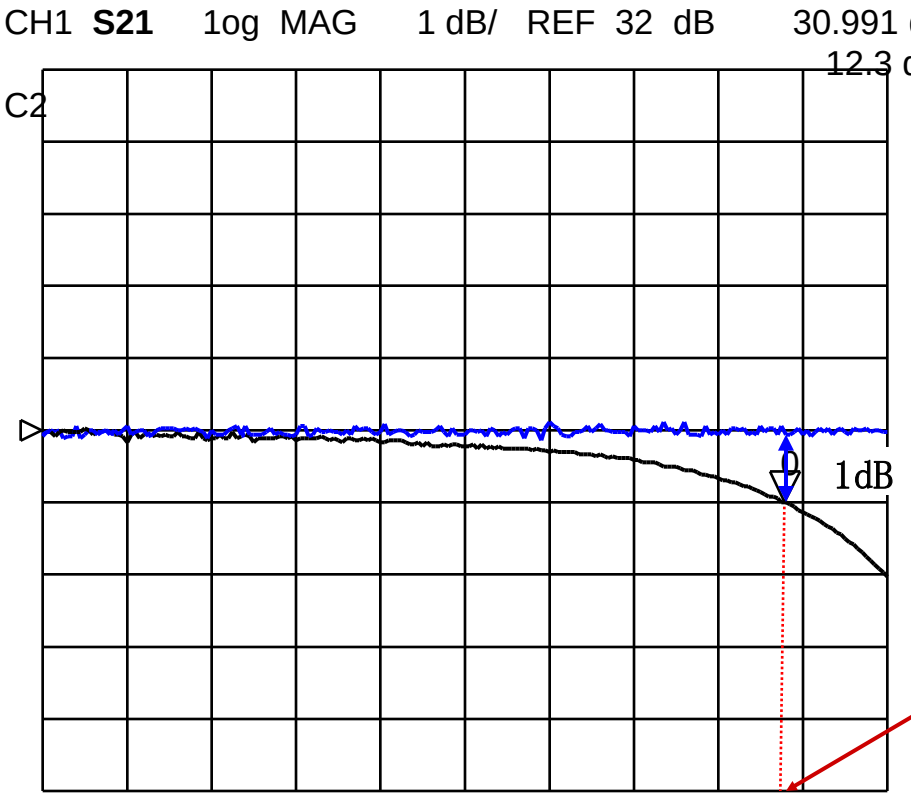
Nonlinear Networks

器件饱和, 串扰, 交调等非线性过程导致传输信号波形失真



器件的功率动态范围:

输入1dB压缩点



1 dB compression point:

输入功率增加导致器件增益下降1dB

- 相对测试
- 输出1dB压缩点(绝对测试)

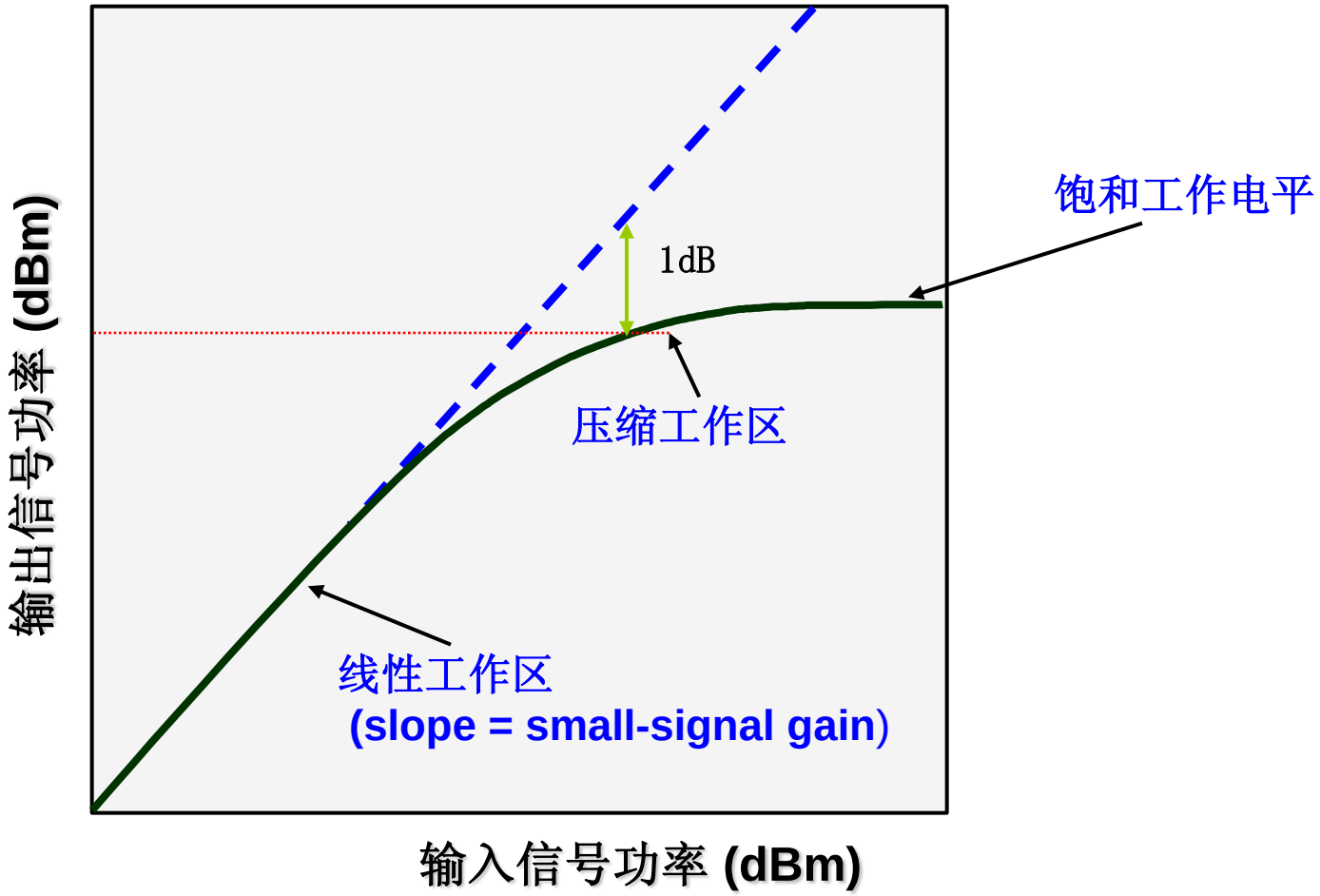
输入1dB压缩点

测试功率

测试频率

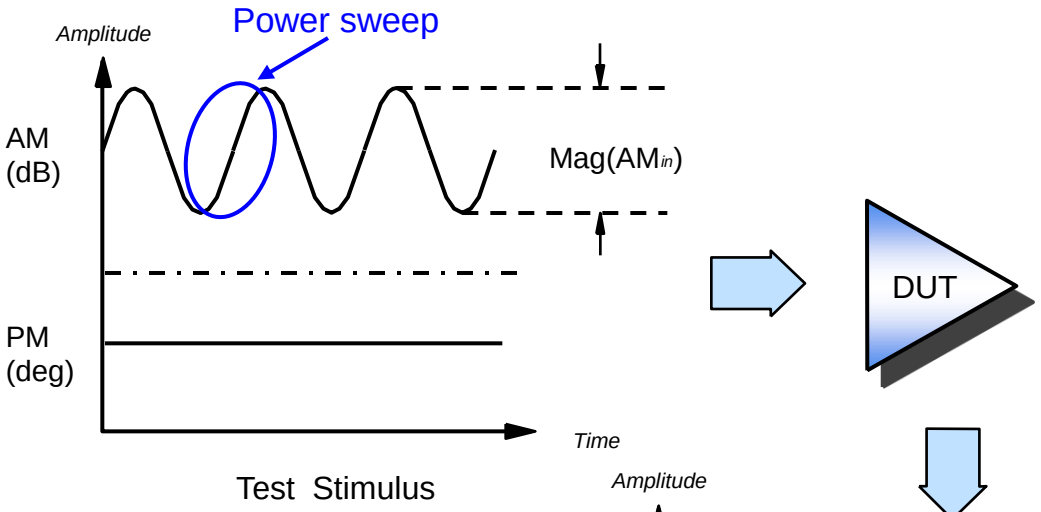
器件的功率动态范围:

输出1dB压缩点



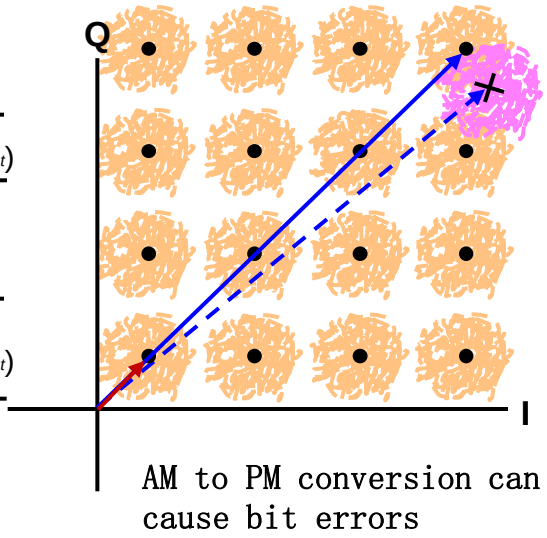
AM / PM 转换对系统的影响

输入功率对器件相位特性的影响



AM - PM Conversion =

$$\frac{Mag(PM_{out})}{Mag(AM_{in})} \quad (deg/dB)$$



网络分析仪

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- 网络分析仪 工作原理
- 误差和校准
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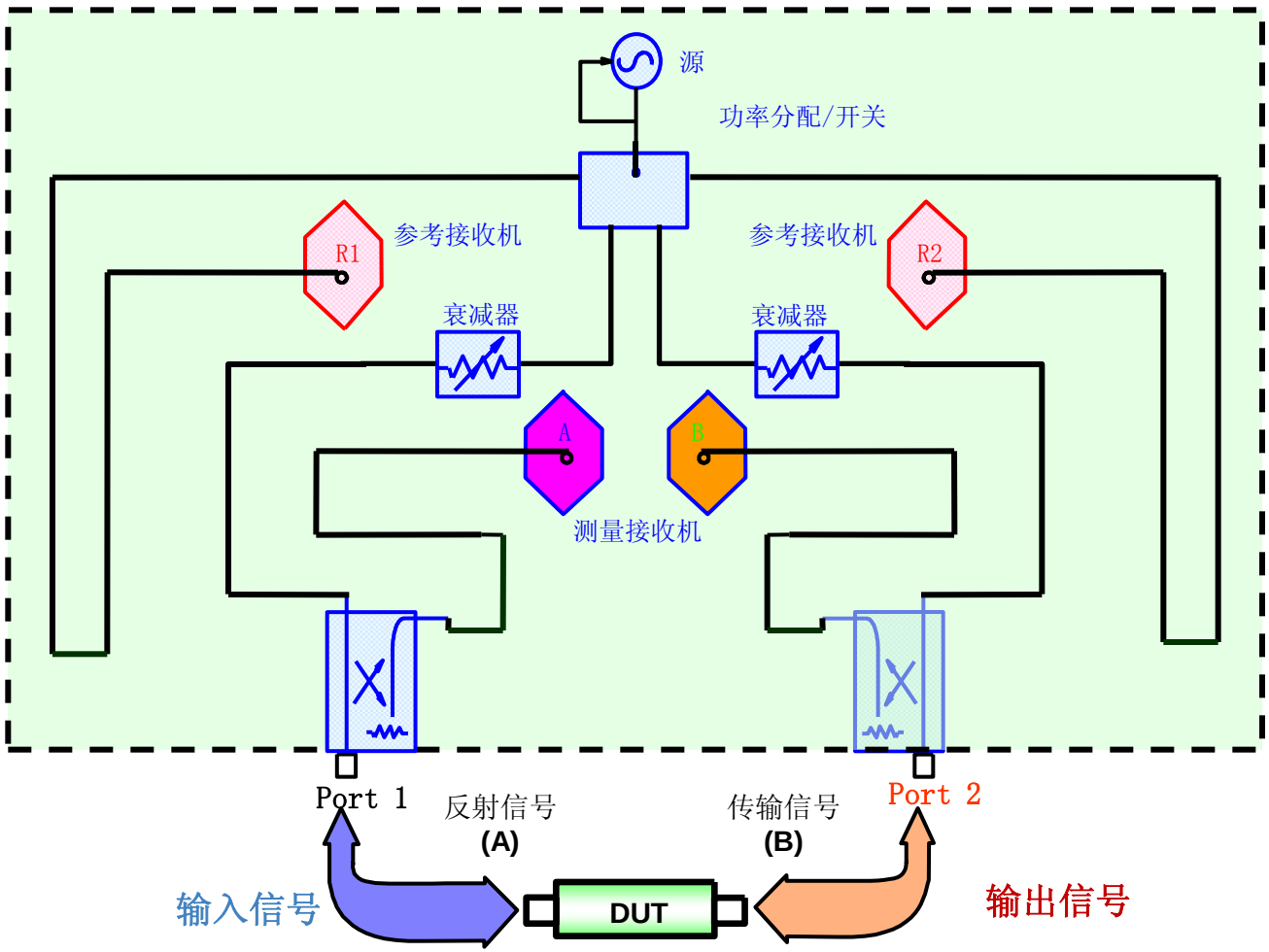
- **PNA**

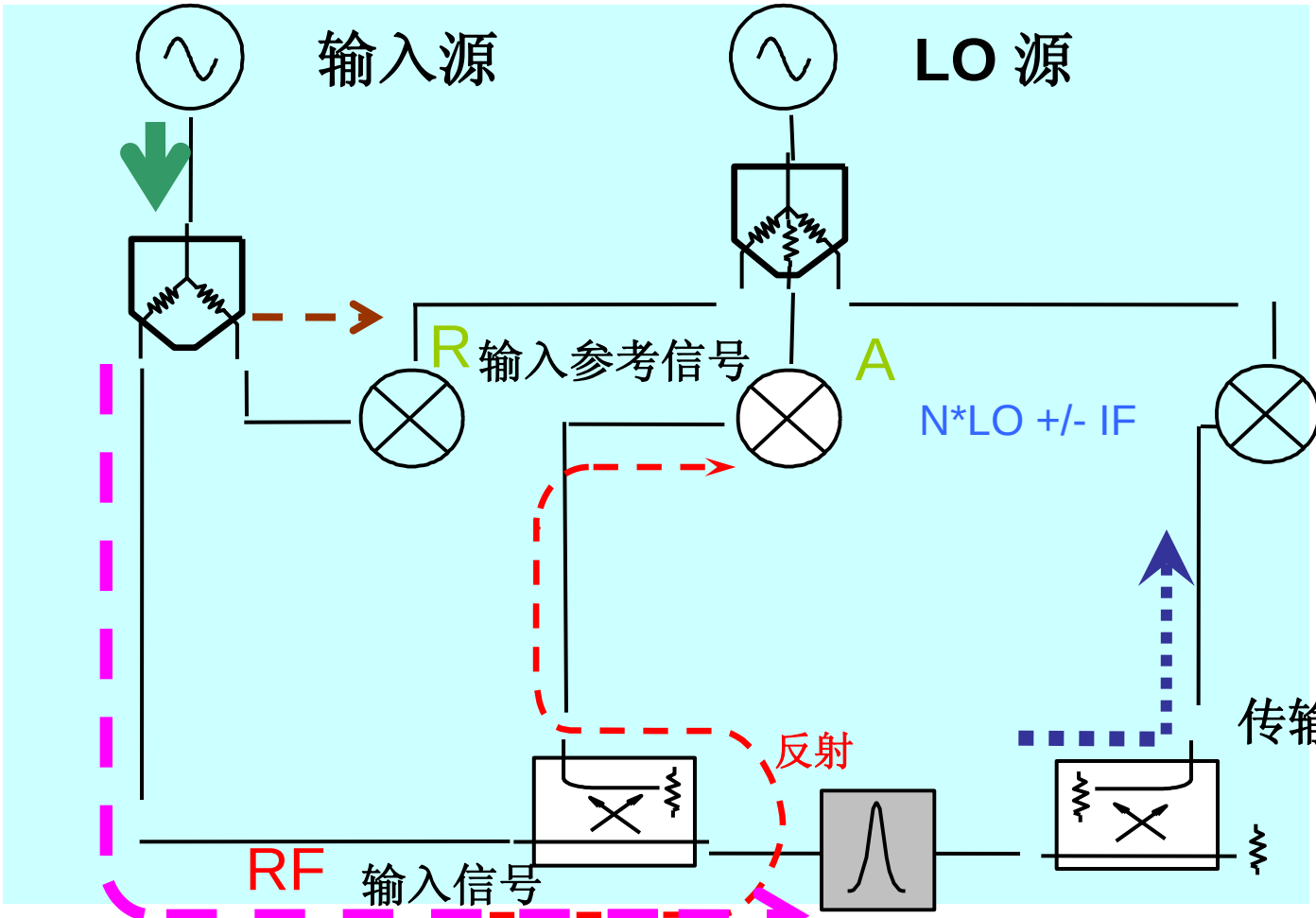
网络分析仪组成框图



网络分析仪组成

- 信号源
- 信号分离装置
- 接收机
- 处理显示单元

网络分析仪测试信号流程

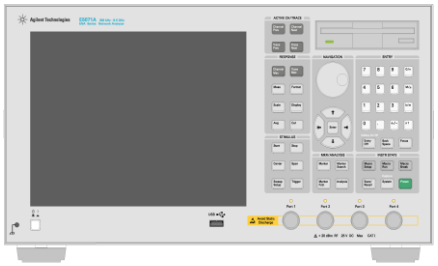


$\frac{A}{R}$:被测件输入端反射特性

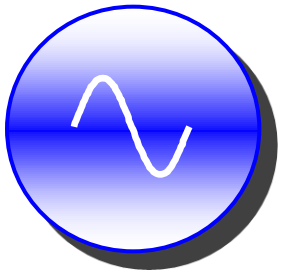
$\frac{B}{R}$:被测件正向传输特性

信号源

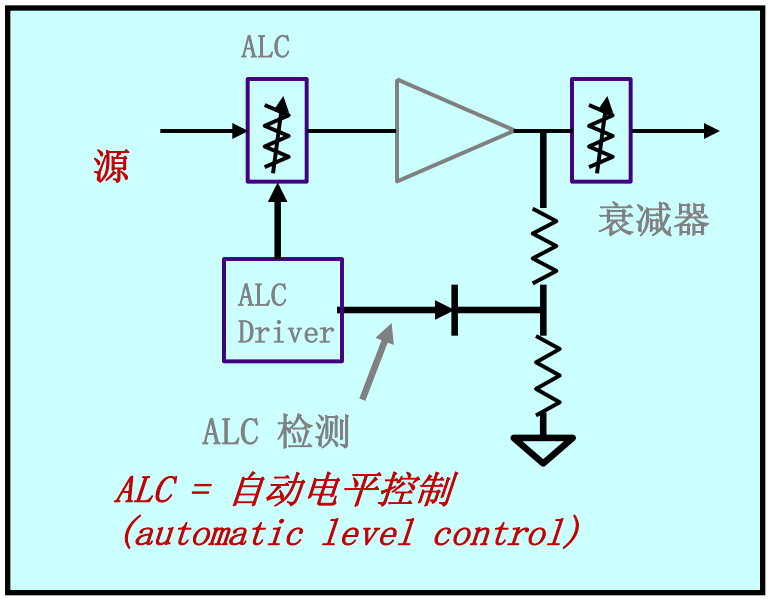
- 提供被测件激励信号
- 具备频率和功率扫描功能
- 合成源实现



频率合成源



源功率控制



源功率控制部分=

ALC：*小范围功率调整，功率扫描*

\+

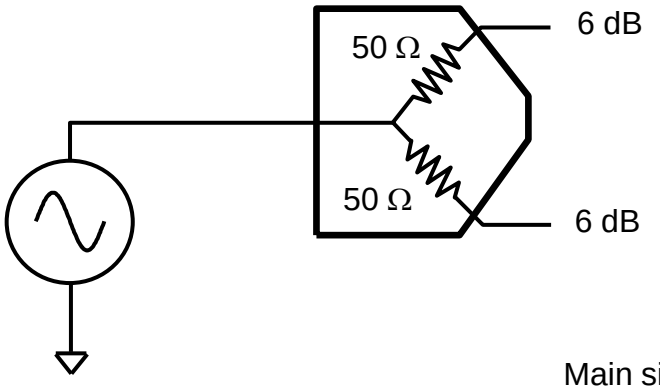
衰减器：*大范围功率调整*

Range1
Range2
Range3
….

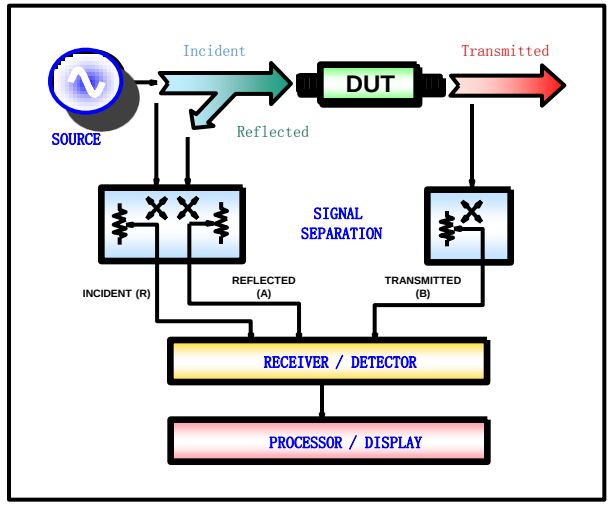
端口稳定点频输出：

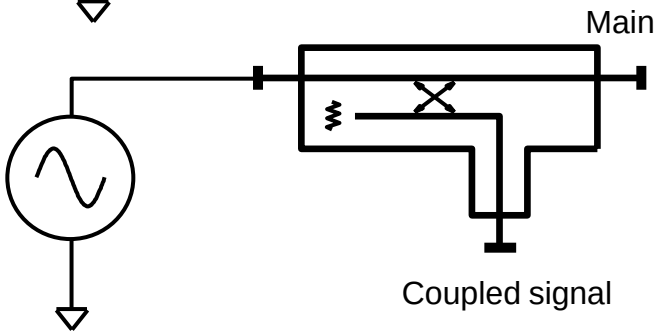
span=0Hz, max sweep time

信号分离装置

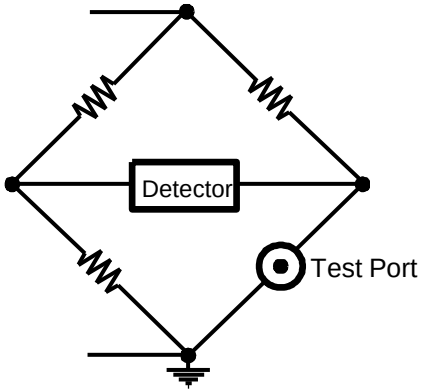


- *功分器*
  - → 提供参考信号
    - → 宽频率覆盖





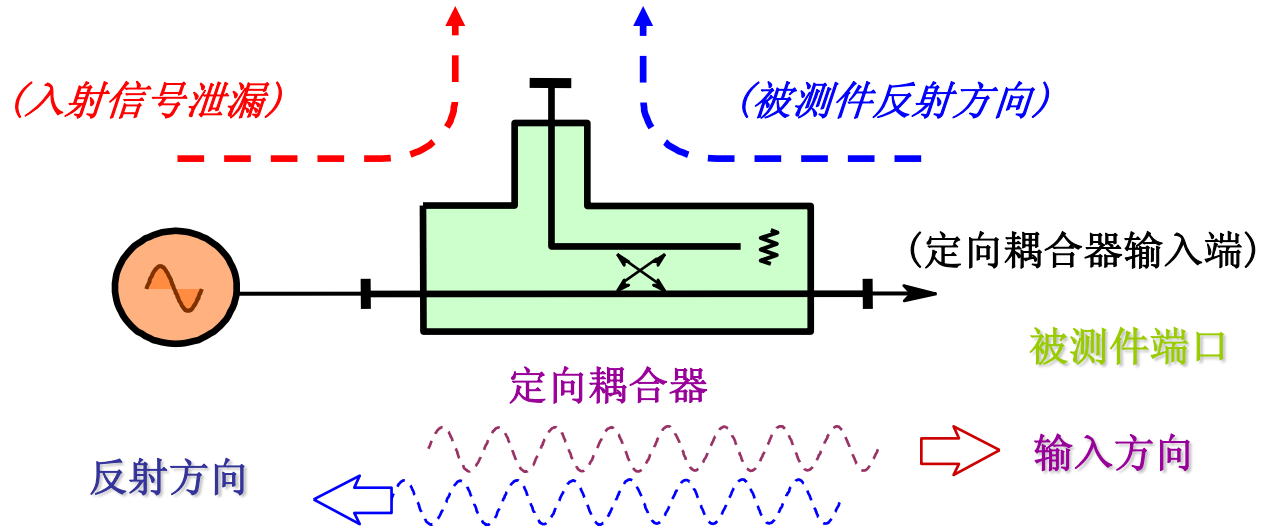
- *定向耦合器*
- *电桥*
  - → 方向性
    - → 低插入损耗



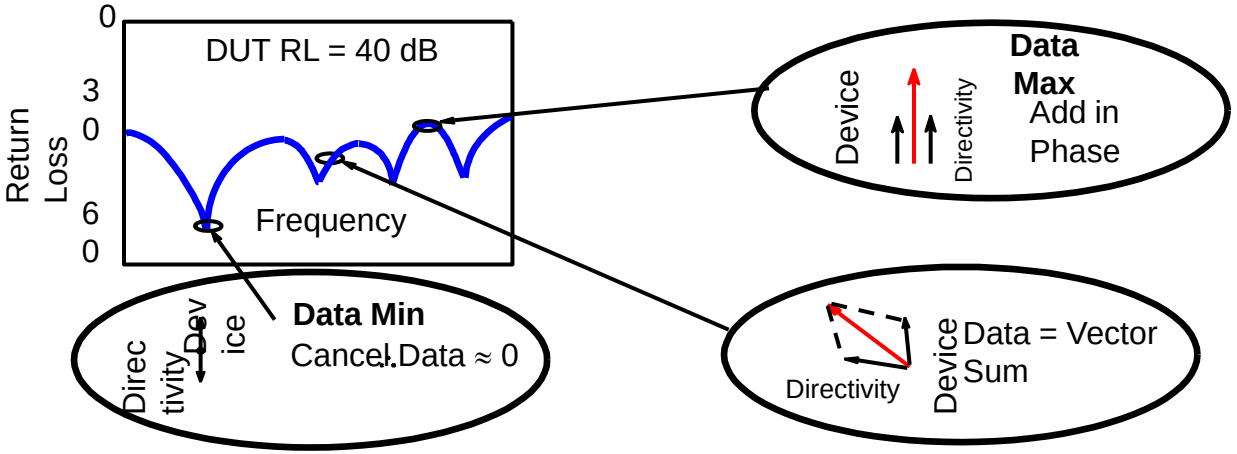
定向耦合器连接端点：反射特性测试点

定向耦合器用于器件反射性能测试

Directivity 方向性
反映定向耦合器
分离两个相反传输
方向信号的能力.



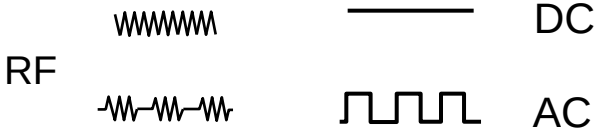
被测件反射信号
与定向耦合器泄漏的
输入信号
在接收机端矢量叠加
影响测试精度

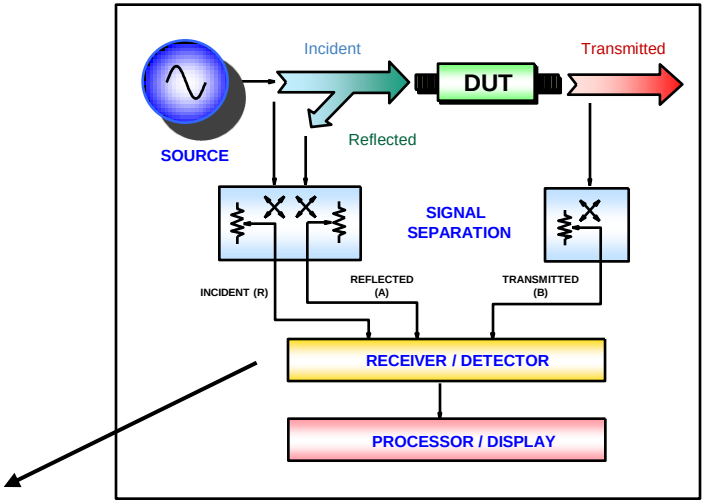


接收机类型

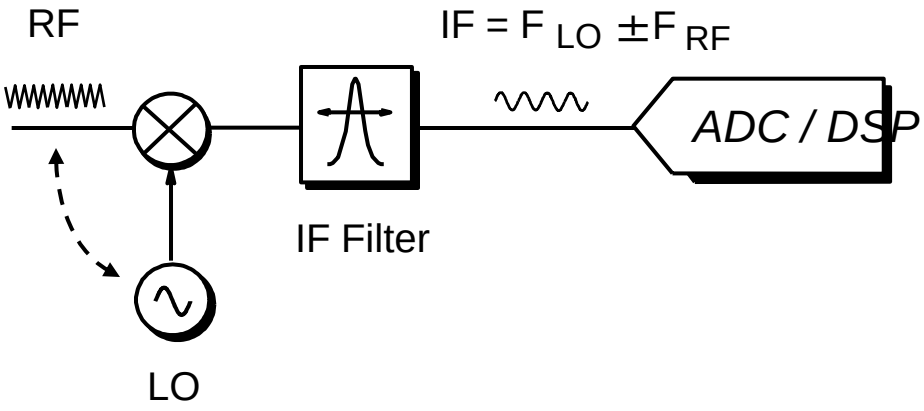
Scalar **broadband**
(no phase
information)

Diode





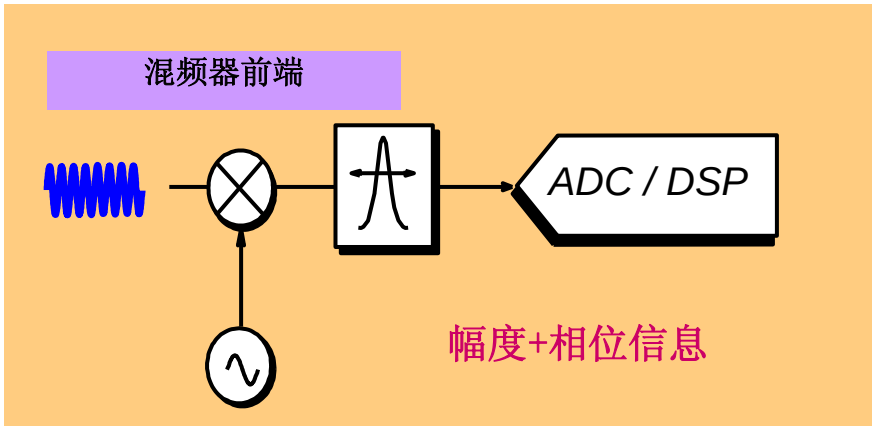
Tuned Receiver

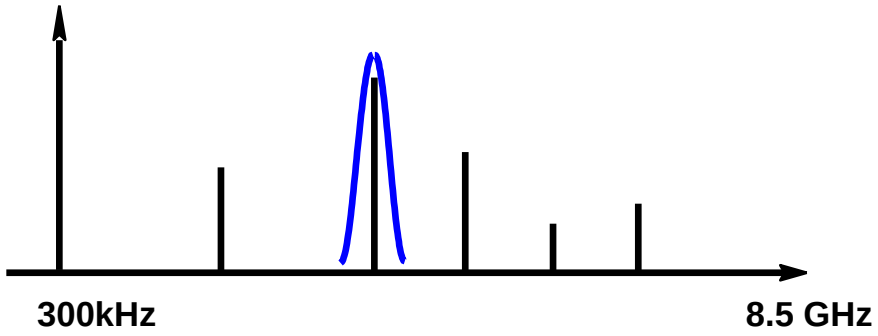


Vector
(magnitude and
phase)

调谐接收机的特点

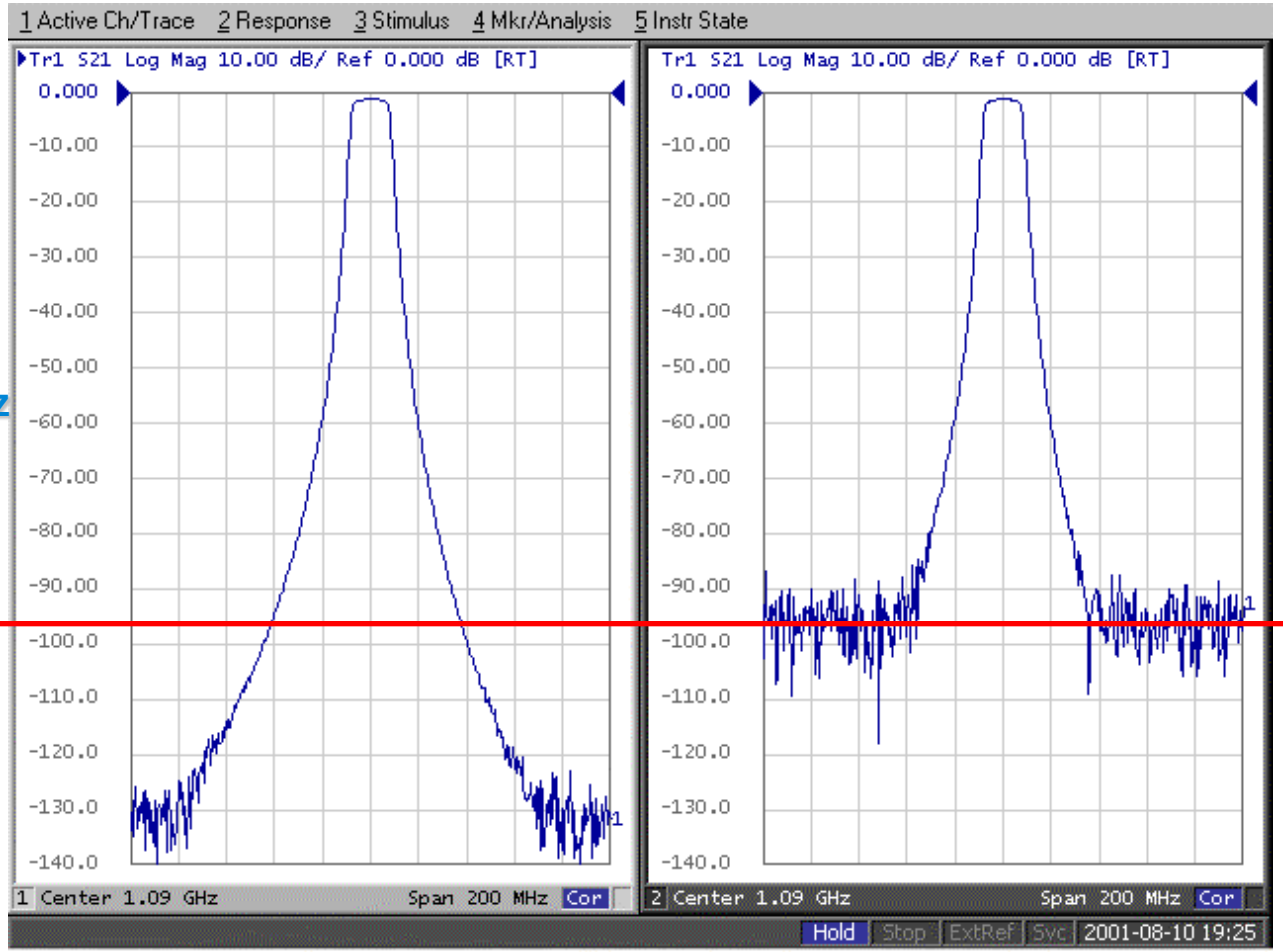
- 高灵敏度接收机
- ENA 采用混频方式接收机
- 接收机噪声电平与其接收带宽有关
- 网络分析仪要求大测试动态范围
- 对被测件输出杂波/谐波有抑制作用
- 接收机带宽在测试动态范围和测试速度间折衷





网络分析仪的测试动态范围

接收机带宽:10Hz



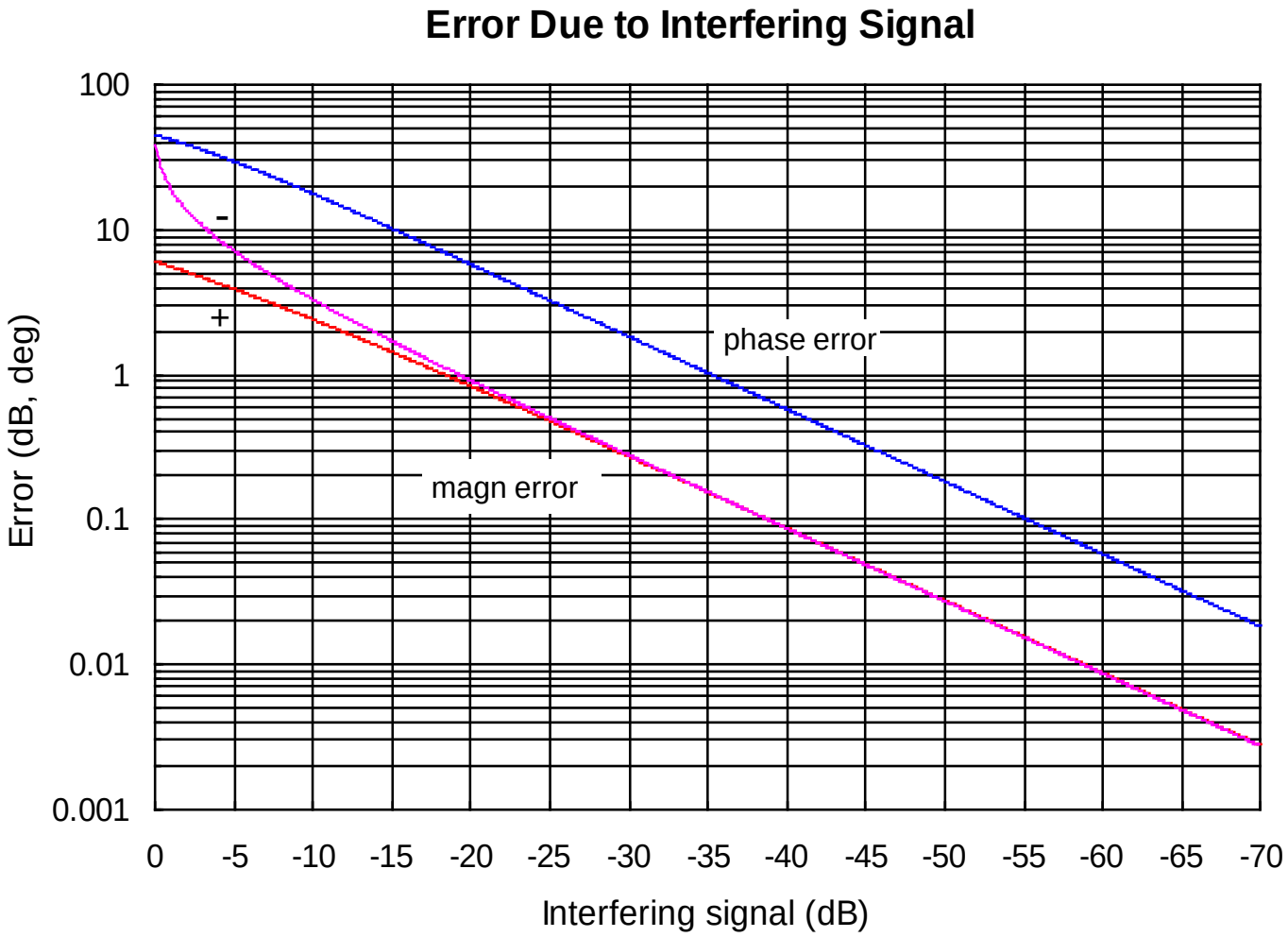
接收机带宽
:70kHz

-100dB

- 接收机噪声电平小, 网络分析测试动态范围大
- 接收机噪声电平高，网络分析测试动态范围小

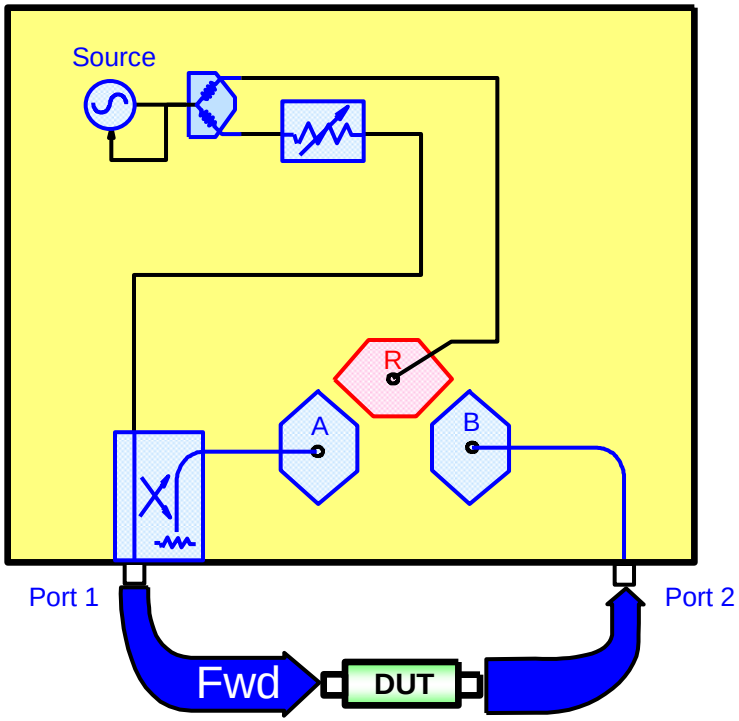
网络分析仪测试动态范围和测试精度

网络分析仪测试精度与测试动态范围关系



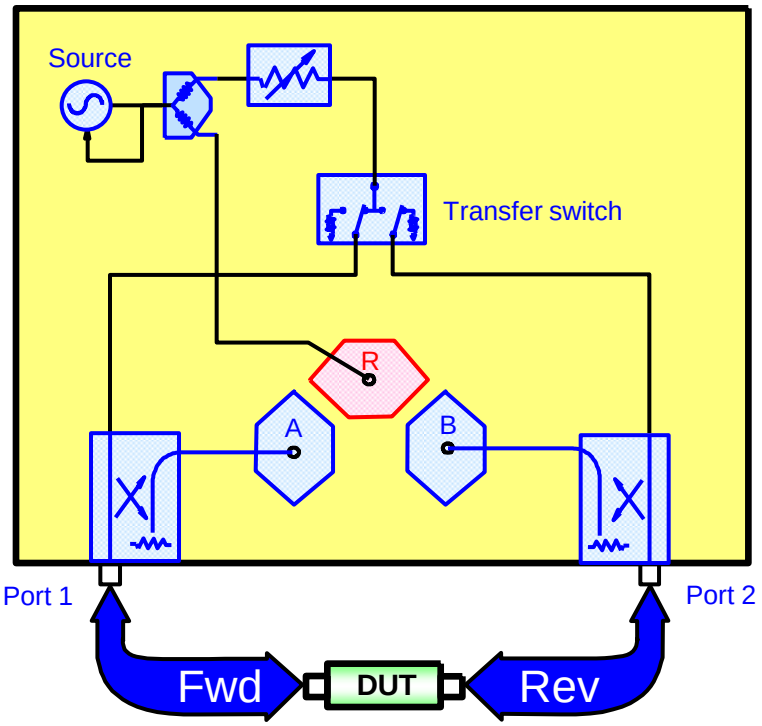
T/R vs S-Parameter Test Sets

Transmission/Reflection Test Set



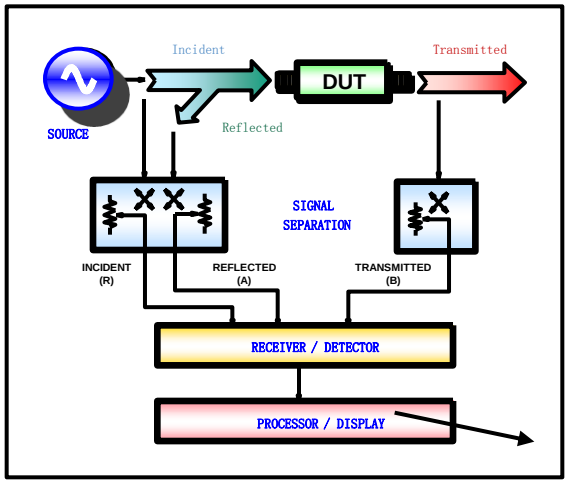
- RF always comes out port 1
- port 2 is always receiver
- **response**, **one-port** cal available

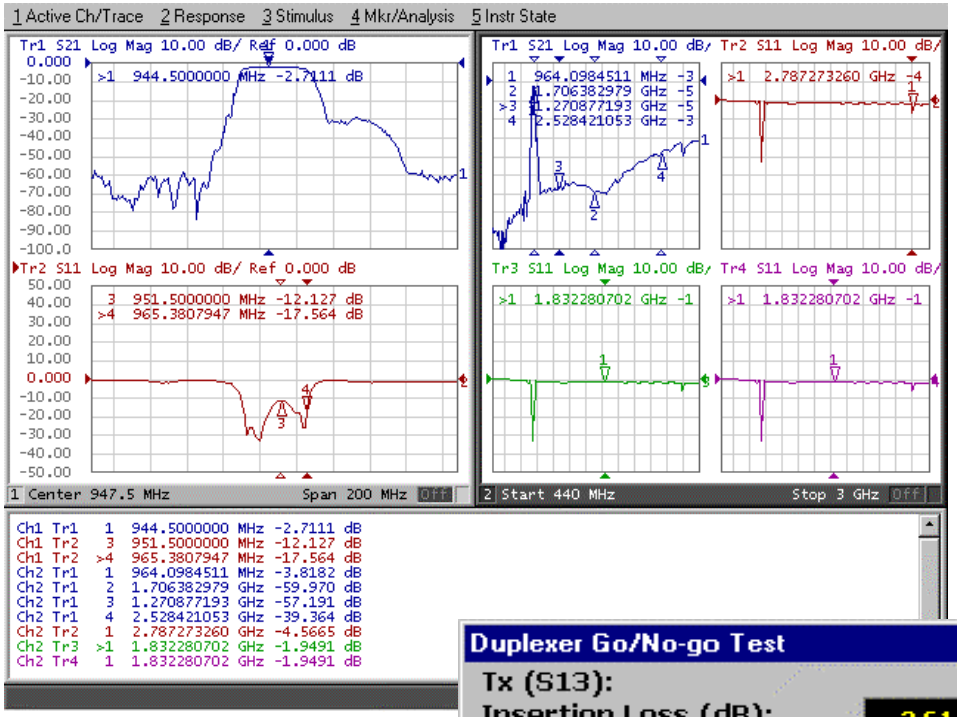
S-Parameter Test Set

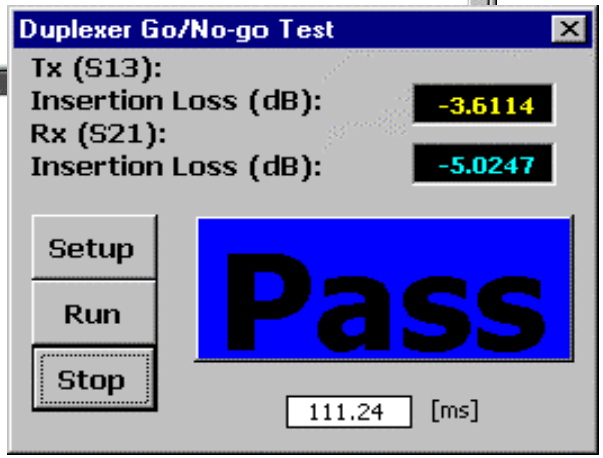


- RF comes out port 1 or port 2
- forward and reverse measurements
- **two-port** calibration possible

显示处理单元







- 标识(marker) 读取测试结果
- 极限判断(limit lines)
- 显示比例和标识
- 文件处理
- ……..

网络分析仪

- 网络分析仪测试基本概念
- 网络分析仪 工作原理
- 误差和校准
- ENA
- PNA

网络分析仪测量误差

系统误差

- 由于测试仪表原理或测试设备引起
- 变化有规律
- 能够被定量描述
- 可通过校准消除

随机误差

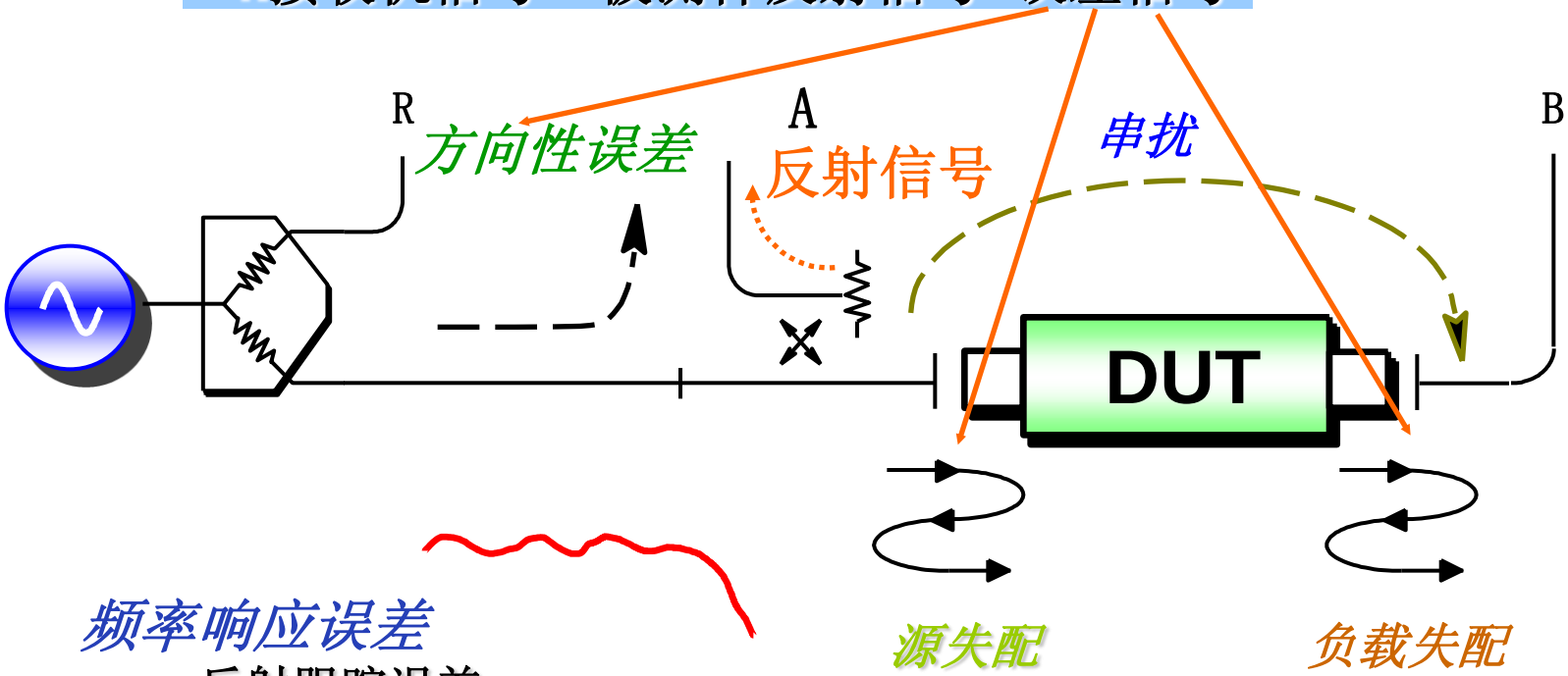
- 随时间随机变化
- 不能通过校准消除
- 引起随机误差的原因：
  - 设备噪声
  - 开关重复性
  - 连接器重复性

飘移误差

- 校准后仪表性能变化
- 主要由温度变化造成
- 通过定期计量消除

反射参数测试误差分析

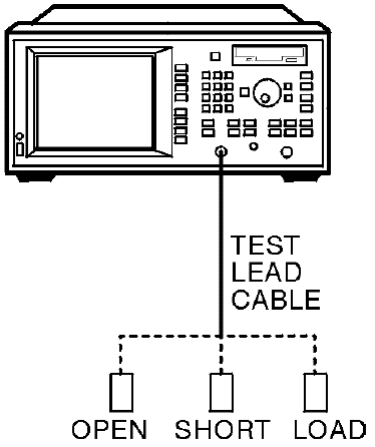
A接收机信号= 被测件反射信号+误差信号



- 反射跟踪误差
- 传输跟踪误差

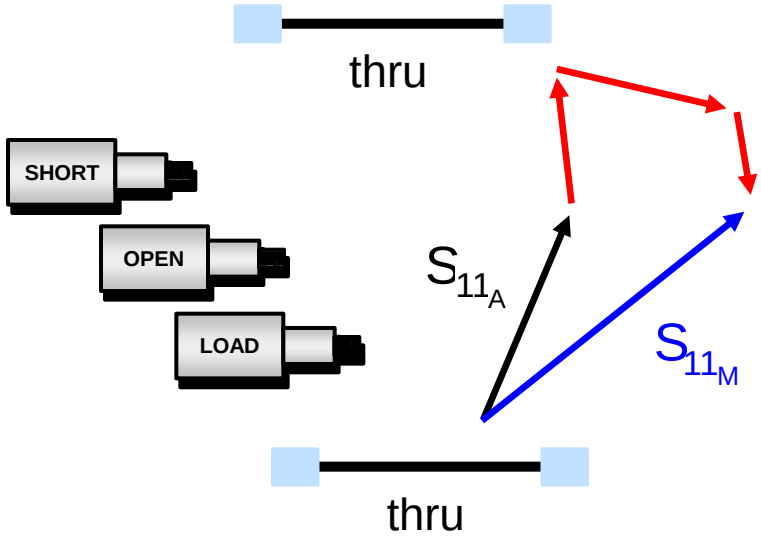
单端口共 6 项误差
双端口共 12 项误差

校准的基本分类

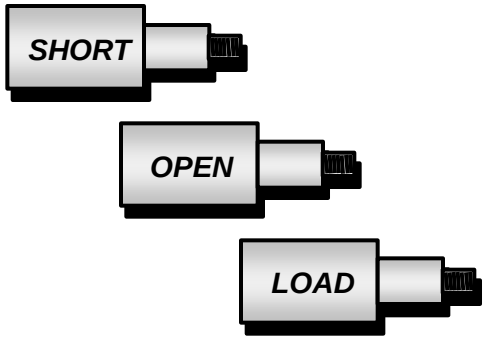


- 频响校准 (response校准)=归一化处理(normalization)
  - 简单
  - 只能消除跟踪误差(频响误差)
  - 相当于归一化处理(Data→mem, Data/mem)

- 矢量校准
  - 需要测试更多校准件
  - 可消除更多误差项目
  - 要求矢量测试能力



校准的概念



- 校准网络分析仪误差的过程
  - 测量参数已知的标准件,得到误差项
  - 将测试结果中误差项成份消除
- 反射测试

  存在三项误差:方向性,源失配, 反射通道频率响应
  - 频响校准(推荐标准件: short)消除频响误差
  - 1-port 单端校准 消除3项误差
- 反射传输测试

  存在12项误差

  频响校准(校准件: through) 消除频响误差

  full 2 port 双端口校准消除12项误差
- cal kit: 定义校准件数据 definition file
- 用户可定义校准件: 校准件定义必须和实际校准件相符

ENA 支持的校准件方式

机械校准件

校准件多次连接
Shorts, Open, Loads, Thru

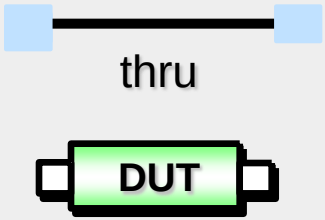
电子校准件(Ecal)

单次连接；多端口校准
Single Connection

不同的校准方法总结

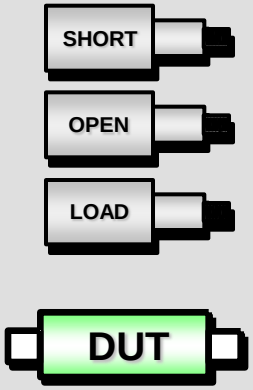
1. 不校准

2. 频响校准



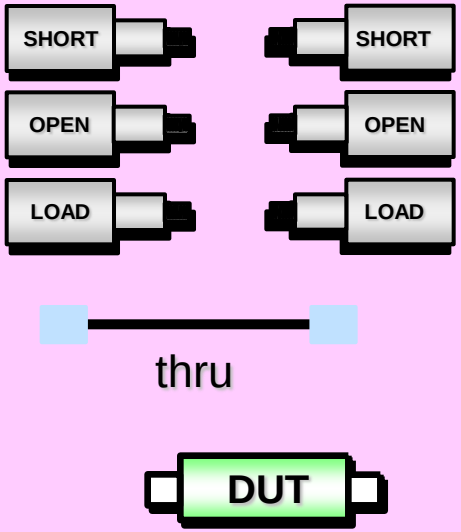
- 方便
- 消除频率相应误差
- 不要求高精度
- 传输测试=直通
- 反射测试=短路

3. 1-PORT单端校准



- 反射测试
- 消除测试端口所有误差
  - Directivity
  - Source match
  - Reflection tracking
- 校准件:
  - open
  - short
  - load

4. FULL 2-PORT双端校准



- 复杂,校准件多次连接
- 高精度
- 消除测试中所有误差:
  - Directivity
  - Source, load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk

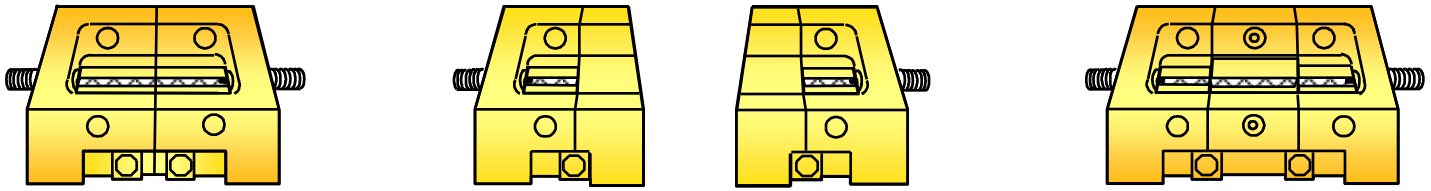
TRL校准

Thru-Reflect-Line

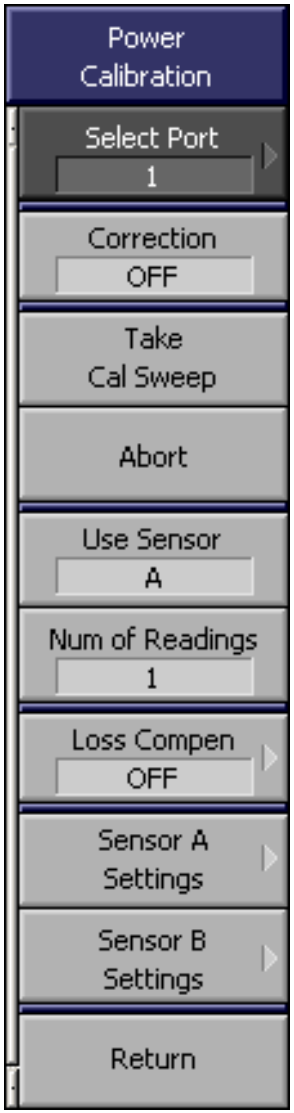
TRL校准的特点:

- 双端口校准技术
- 适合非同轴系统测试 (waveguide, fixtures, wafer probing)
- 与SOLT 校准使用相同的12项误差模型
- 要求网络分析仪 4 接收机, 3 接收机支持TRL*校准

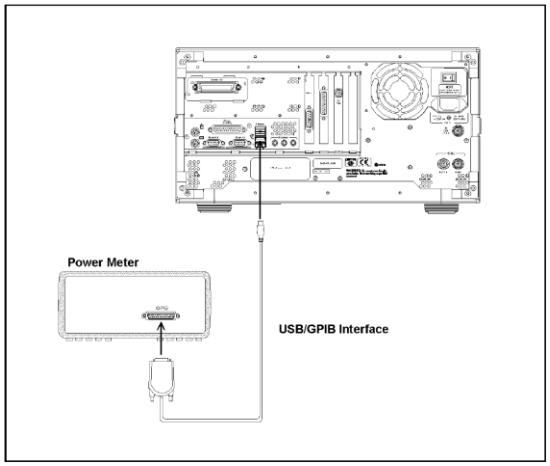
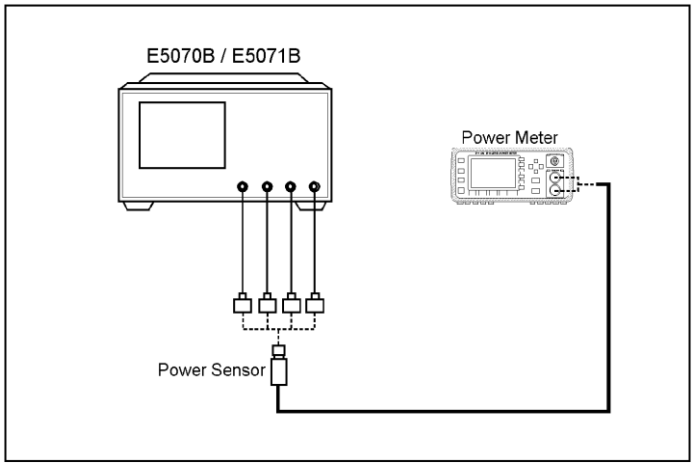
- 其它校准方法:
- Line-Reflect-Match (LRM), Thru-Reflect-Match (TRM)



网络仪功率校准确保源功率精度



- 保证测试端口输出功率准确
- 不同测试通道和测试端口分别设置

- 与ENA兼容的功率计

437B	(Single ch)
438A	(Dual ch)
EPM-441A	(Single ch)
EPM-442A	(Dual ch)
E4416A	(Single ch)
E4417A	(Dual ch)
E4418A	(Single ch)
E4418B	(Single ch)
E4419A	(Dual ch)
E4419B	(Dual ch)