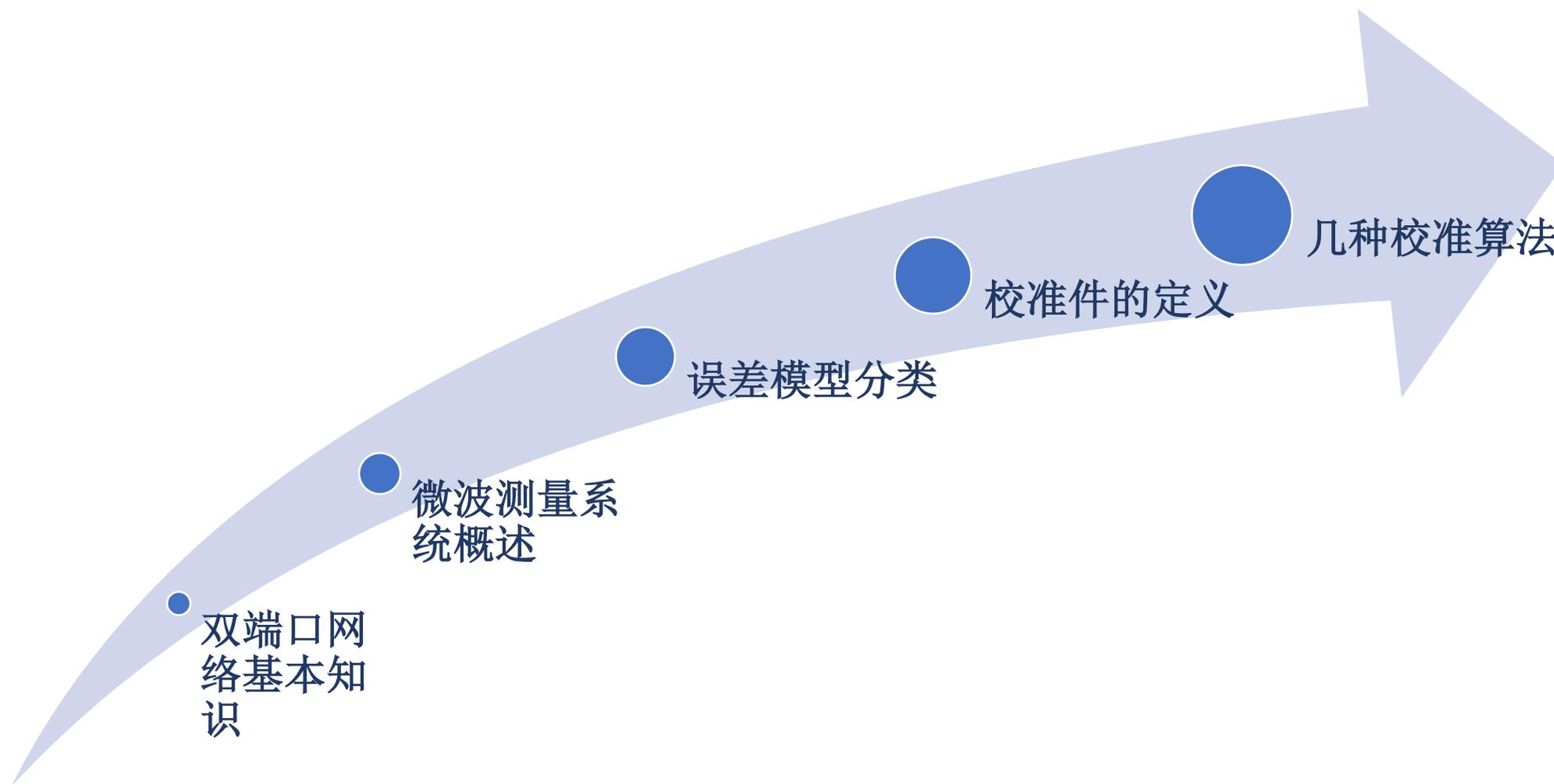


# 微波设计与综合测量实验

——在片测量和VNA校准算法

(4课时)

# 基本授课思路

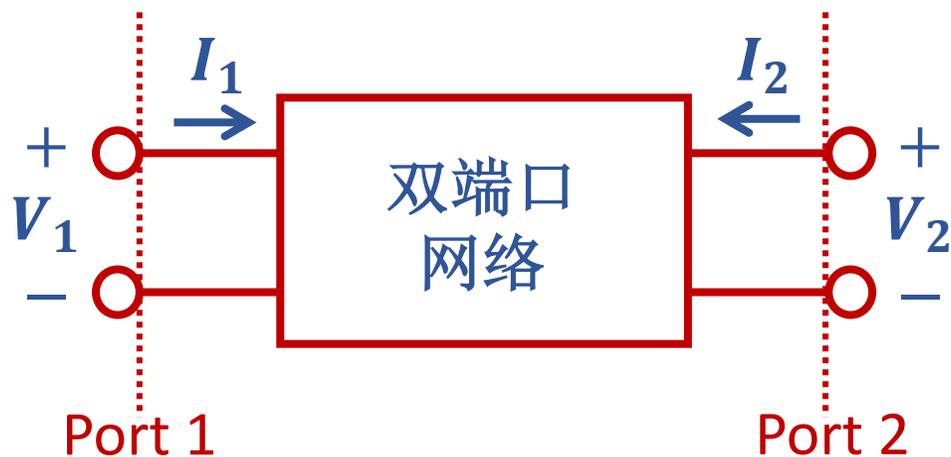


# 基本知识回顾

- 双端口网络
- S参数
- ACBD参数
- T参数
- 参考阻抗

# 双端口网络

线性网络可以完全由端口处所测得的参数表征，而无需知道网络内部情况



双端口表征参数：Z, Y, R, T, S, ABCD等

双端口矩阵：2个独立激励变量  
2个独立反应变量

# 网络分析仪 (VNA)

VNA 将电路元件表示为frequency的函数，便于分析电路的频率依存性：

- ✓ 输入信号是扫频正弦信号
- ✓ 电压和电流难以直接测量
- ✓ 通过传输和反射的功率表征电路网络  
--S参数



# S参数

通过传输和反射波的功率表征电路网络

$a_i$ 和 $b_j$ 的定义为:

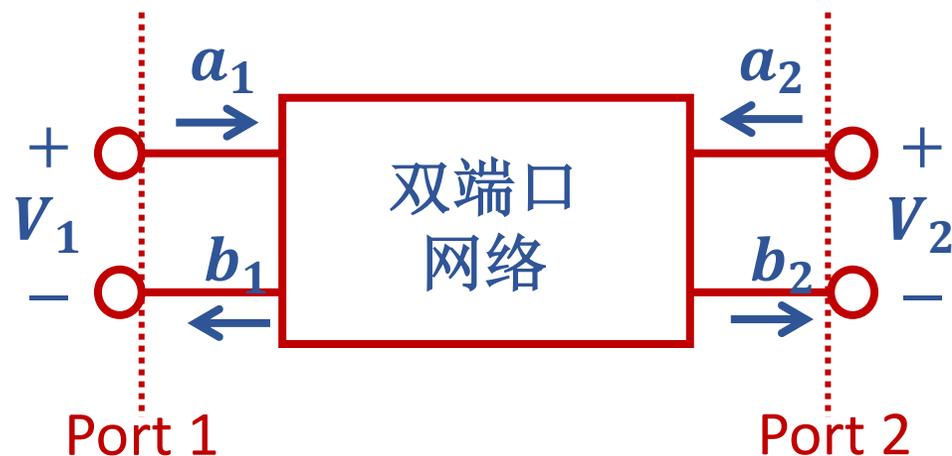
$$a_i = \sqrt{P} = \frac{V_i^+}{\sqrt{R}} \quad P = V^2 / R$$

$$b_i = \sqrt{P} = \frac{V_i^-}{\sqrt{R}}$$

$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$

$$S_{ij} = \frac{b_j}{a_i} = \frac{\text{端口 } j \text{ 的功率}}{\text{端口 } i \text{ 的功率}}$$



# S参数的优缺点

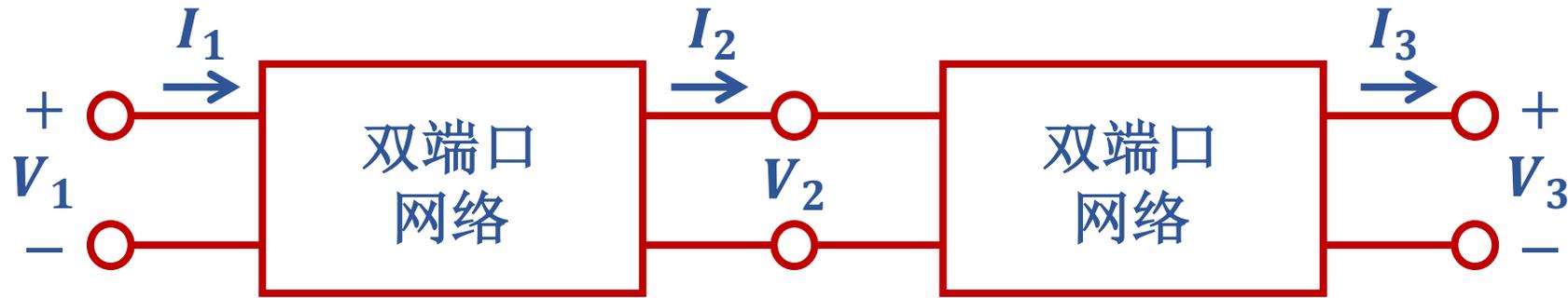
## 优点:

- ✓ 基于功率测量很容易实现，尤其在高频

## 缺点:

- ✓ 测量结果难以理解，更难以解释

# ABCD参数



$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_1 \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_2 \begin{bmatrix} V_3 \\ I_3 \end{bmatrix}$$

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_1 \begin{bmatrix} A & B \\ C & D \end{bmatrix}_2 \begin{bmatrix} V_3 \\ I_3 \end{bmatrix}$$

基于电流电压计算，简单精确，是频域内**最好用的级联矩阵**！

# ABCD参数与S参数之间的转化

当电源端和负载端的特性阻抗相同，且都为 $Z_0$ 时：

<i>S</i>	
<i>A</i>	$\frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{2S_{21}}$
<i>B</i>	$Z_0 \frac{(1 + S_{11})(1 + S_{22}) - S_{12}S_{21}}{2S_{21}}$
<i>C</i>	$\frac{1}{Z_0} \frac{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}}{2S_{21}}$
<i>D</i>	$\frac{(1 - S_{11})(1 + S_{22}) - S_{12}S_{21}}{2S_{21}}$

<i>ABCD</i>	
$S_{11}$	$\frac{A + B/Z_0 - CZ_0 - D}{A + B/Z_0 + CZ_0 + D}$
$S_{12}$	$\frac{2(AD - BC)}{A + B/Z_0 + CZ_0 + D}$
$S_{21}$	$\frac{2}{A + B/Z_0 + CZ_0 + D}$
$S_{22}$	$\frac{-A + B/Z_0 - CZ_0 + D}{A + B/Z_0 + CZ_0 + D}$

# ABCD矩阵优缺点

## 优点:

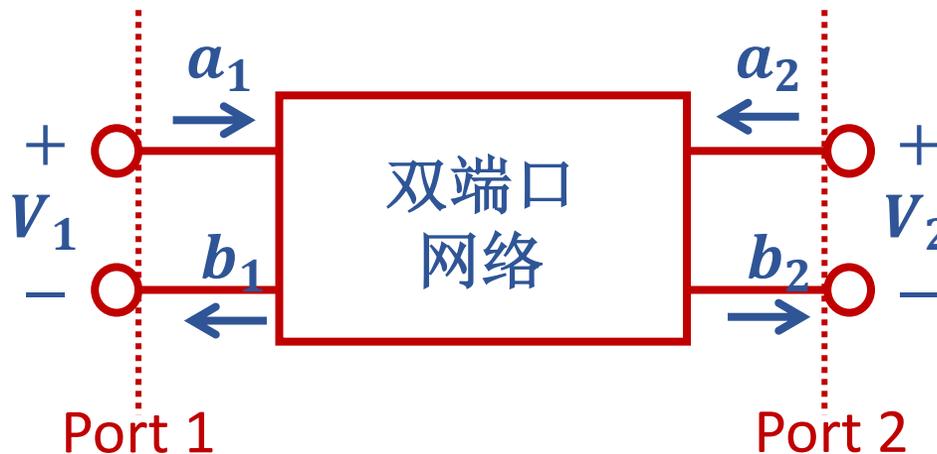
- ✓ 基于电压和电流描述所有端口，直观
- ✓ 非常方便网络之间的级联计算
- ✓ 很容易与S矩阵相互转换.
- ✓ 很容易与常见的电路分析方法相结合

## 缺点:

- ✓ 难以直接测量，须由测得的S矩阵转化获得

# 级联T矩阵

当不考虑阻抗匹配问题时，常用T矩阵



$$\begin{bmatrix} b_i(Z_{ref}^i) \\ a_i(Z_{ref}^i) \end{bmatrix} = T^{ij} \begin{bmatrix} a_j(Z_{ref}^j) \\ b_j(Z_{ref}^j) \end{bmatrix}$$

*How?*

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$T = \frac{1}{S_{21}} \begin{bmatrix} S_{12}S_{21} - S_{11}S_{22} & S_{11} \\ -S_{22} & 1 \end{bmatrix}$$

$$S = \frac{1}{T_{22}} \begin{bmatrix} T_{12} & T_{11}T_{22} - T_{12}T_{21} \\ 1 & -T_{21} \end{bmatrix}$$

$a_i$  和  $b_j$  仍然基于  $\sqrt{P}$ ，不易理解；且用时需注意参考阻抗

# 不同参数之间的转化？

$$\begin{bmatrix} b_1 \\ a_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}$$

$$b_1 = T_{11}a_2 + T_{12}b_2$$

$$a_1 = T_{21}a_2 + T_{22}b_2$$

**T to S**



$$b_1 = T_{11}a_2 + T_{12}(a_1 - T_{21}a_2)/T_{22}$$

$$b_2 = (a_1 - T_{21}a_2)/T_{22}$$



$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$

**S to T**



$$b_1 = S_{11}(b_2 - S_{22}a_2)/S_{21} + S_{12}a_2$$

$$a_1 = (b_2 - S_{22}a_2)/S_{21}$$



# 参数之间转换关系

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

$$\begin{bmatrix} b_1 \\ a_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}$$

$S_{11} = \frac{T_{12}}{T_{22}}$	$T_{11} = \frac{S_{12}S_{21} - S_{11}S_{22}}{S_{21}}$
$S_{12} = \frac{T_{11}T_{22} - T_{12}T_{21}}{T_{22}}$	$T_{12} = \frac{S_{11}}{S_{21}}$
$S_{21} = \frac{1}{T_{22}}$	$T_{21} = \frac{-S_{22}}{S_{21}}$
$S_{22} = \frac{-T_{21}}{T_{22}}$	$T_{22} = \frac{1}{S_{21}}$

# 参数之间转换关系

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}$$

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$$

$$\begin{bmatrix} v_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} v_2 \\ -i_2 \end{bmatrix}$$

$Z_{11} = \frac{Y_{22}}{Y_{11}Y_{22} - Y_{12}Y_{21}}$ $Z_{12} = \frac{-Y_{12}}{Y_{11}Y_{22} - Y_{12}Y_{21}}$ $Z_{21} = \frac{-Y_{21}}{Y_{11}Y_{22} - Y_{12}Y_{21}}$ $Z_{22} = \frac{Y_{11}}{Y_{11}Y_{22} - Y_{12}Y_{21}}$	$Y_{11} = \frac{Z_{22}}{Z_{11}Z_{22} - Z_{12}Z_{21}}$ $Y_{12} = \frac{-Z_{21}}{Z_{11}Z_{22} - Z_{12}Z_{21}}$ $Y_{21} = \frac{-Z_{21}}{Z_{11}Z_{22} - Z_{12}Z_{21}}$ $Y_{22} = \frac{Z_{11}}{Z_{11}Z_{22} - Z_{12}Z_{21}}$
$Z_{11} = \frac{A}{C}$ $Z_{12} = \frac{AD - BC}{C}$ $Z_{21} = \frac{1}{C}$ $Z_{22} = \frac{D}{C}$	$A = \frac{Z_{11}}{Z_{21}}$ $B = \frac{Z_{11}Z_{22} - Z_{12}Z_{21}}{Z_{21}}$ $C = \frac{1}{Z_{21}}$ $D = \frac{Z_{22}}{Z_{21}}$
$Y_{11} = \frac{D}{B}$ $Y_{12} = \frac{BC - AD}{B}$ $Y_{21} = \frac{-1}{B}$ $Y_{22} = \frac{A}{B}$	$A = \frac{-Y_{22}}{Y_{21}}$ $B = \frac{-1}{Y_{21}}$ $C = \frac{Y_{12}Y_{21} - Y_{11}Y_{22}}{Y_{21}}$ $D = \frac{-Y_{11}}{Y_{21}}$

*ABCD-S* 转换关系如何推导?



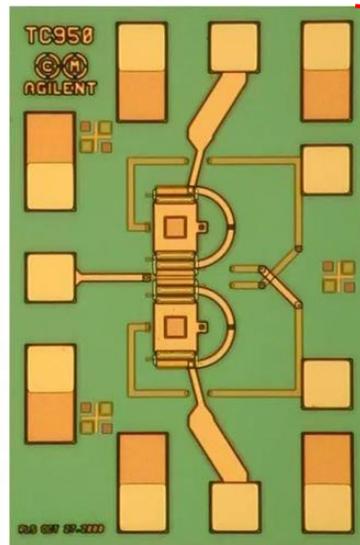
# 基本概念

- 网络分析仪
- 同轴线
- 波导
- 共面波导
- 探针

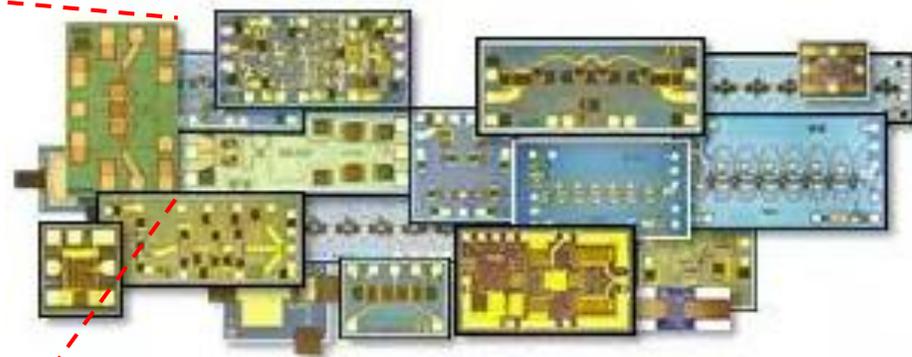
# 网络分析仪

分标量&矢量网络分析仪...

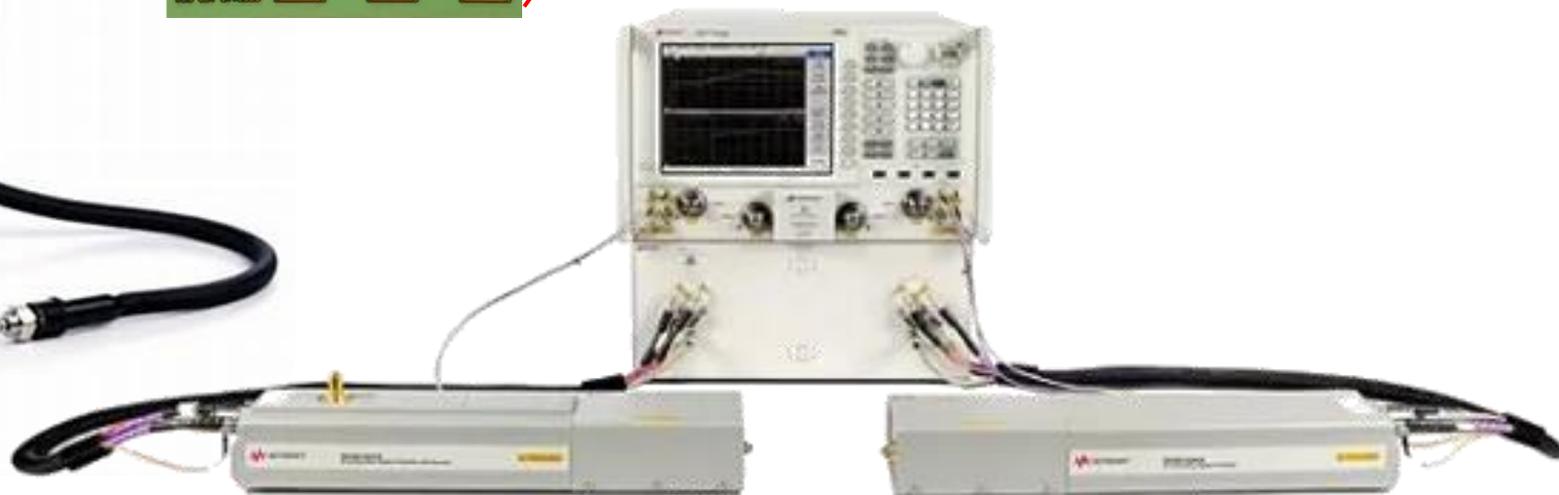
双端口测试连接



全能大boss: PNA-X

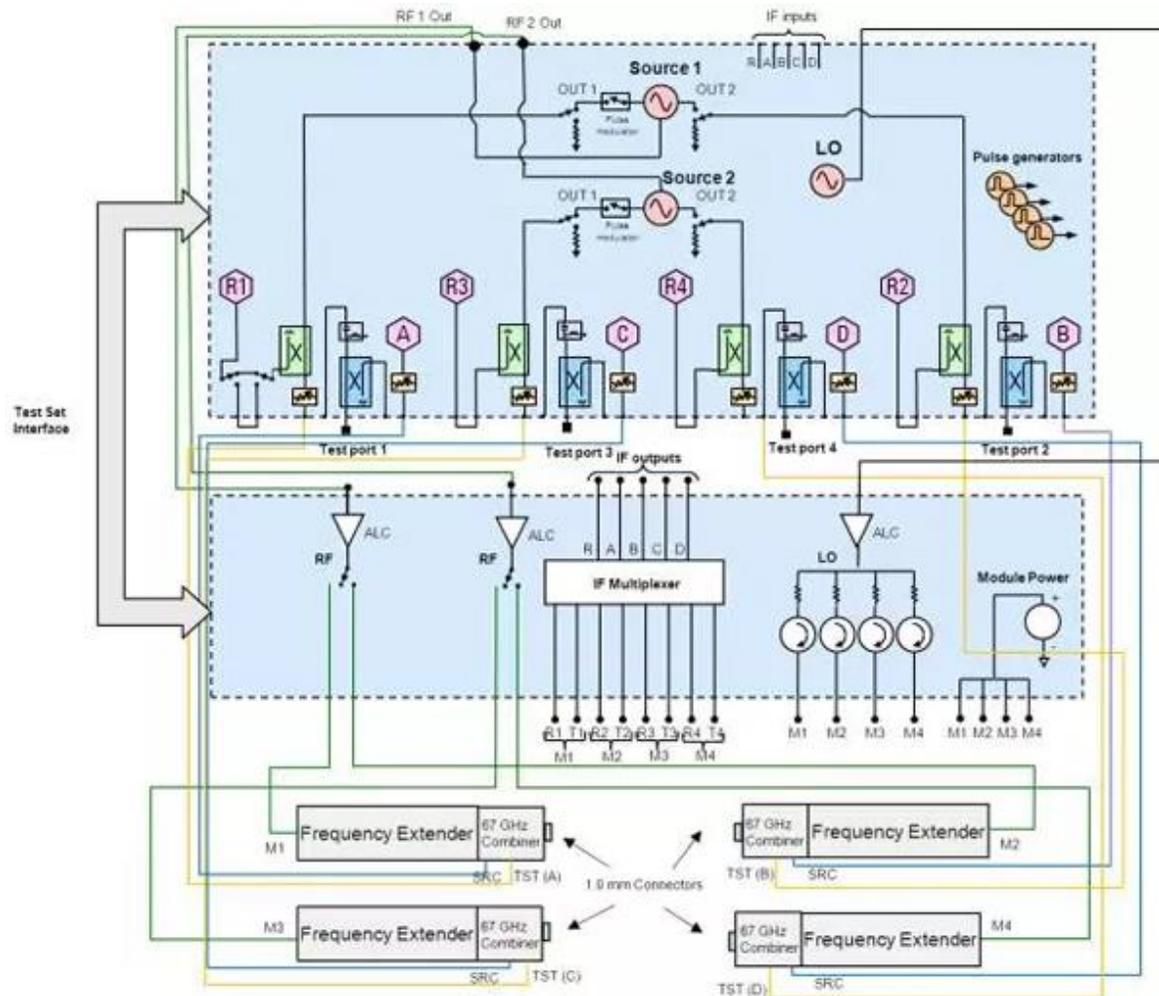
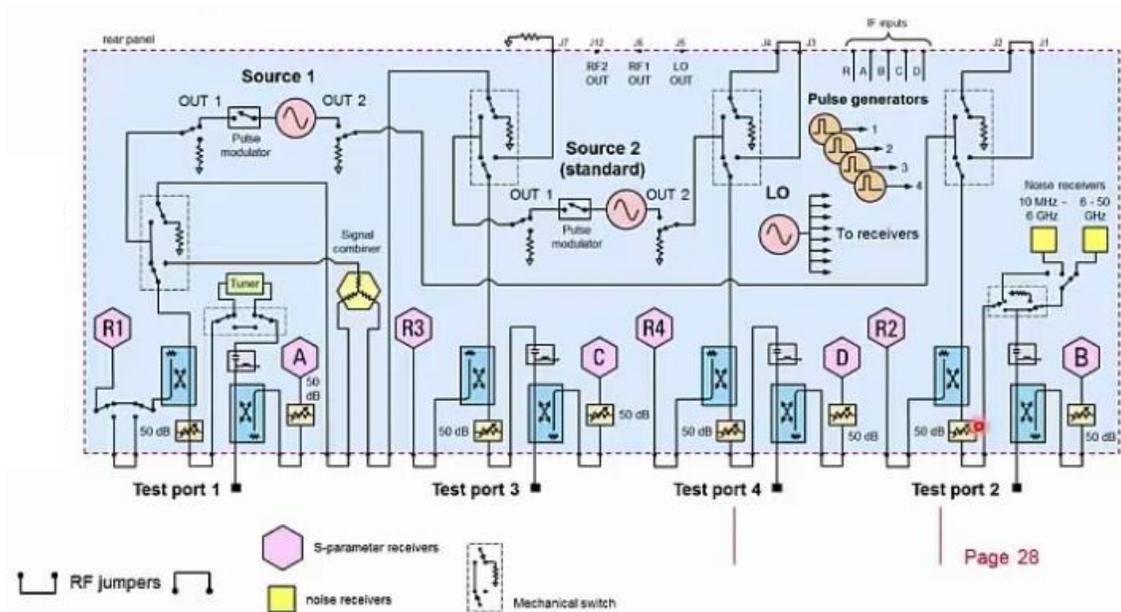


高频矢网+扩展模块扩频



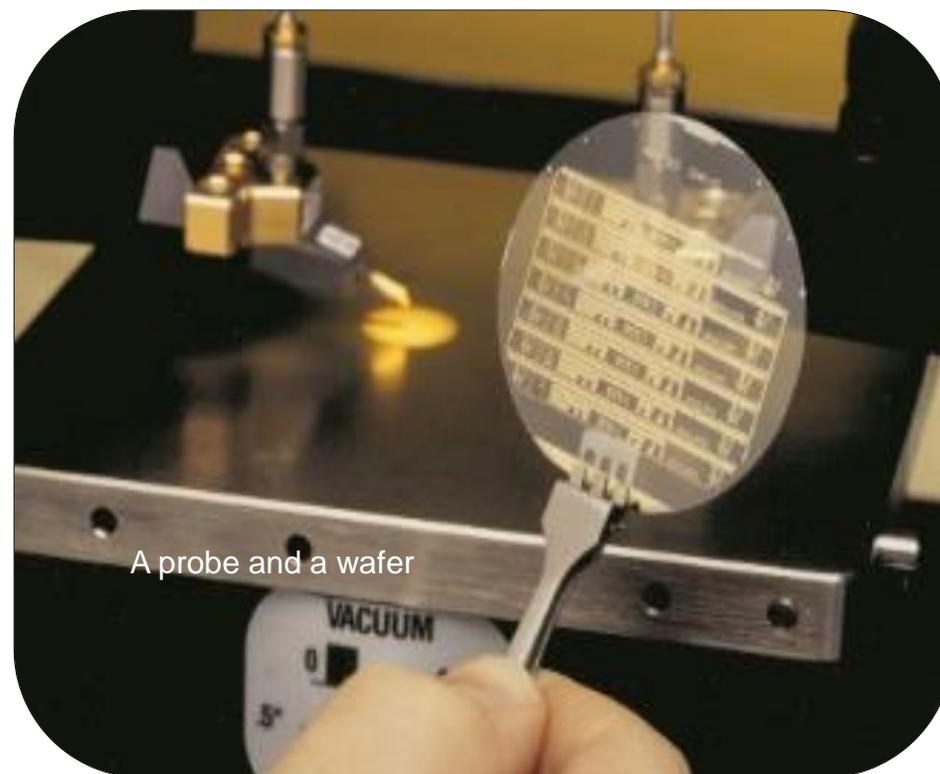
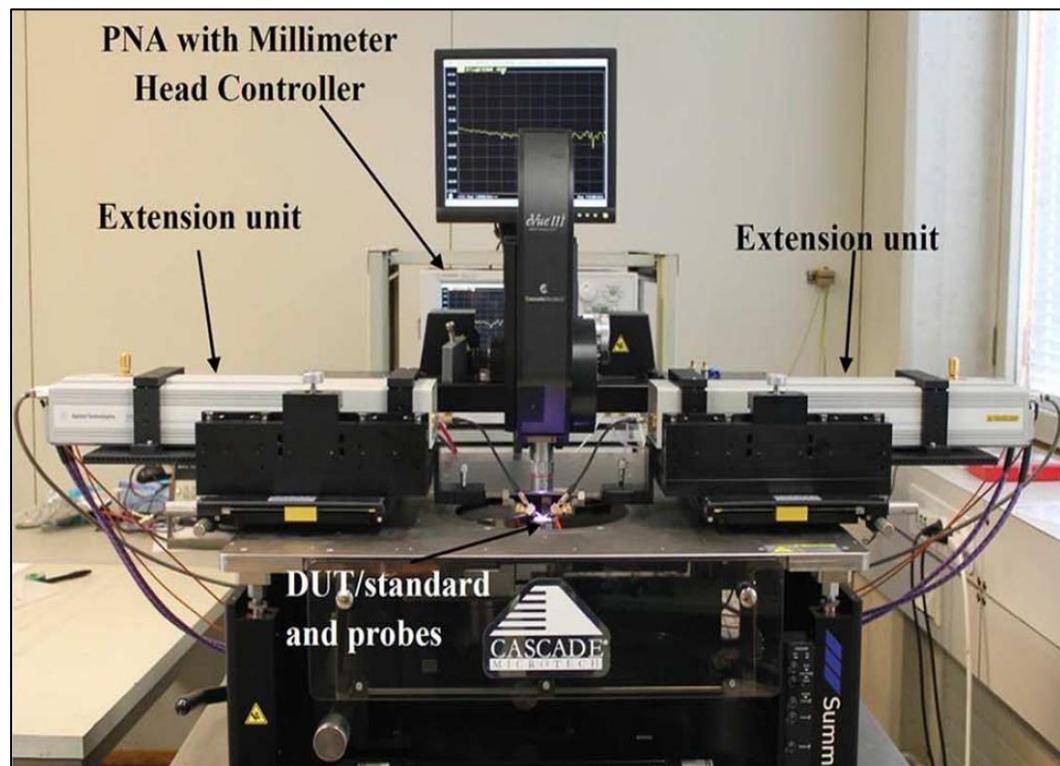
# VNA和扩展模块

4端口VNA的框图和  
加入扩展模块的框图

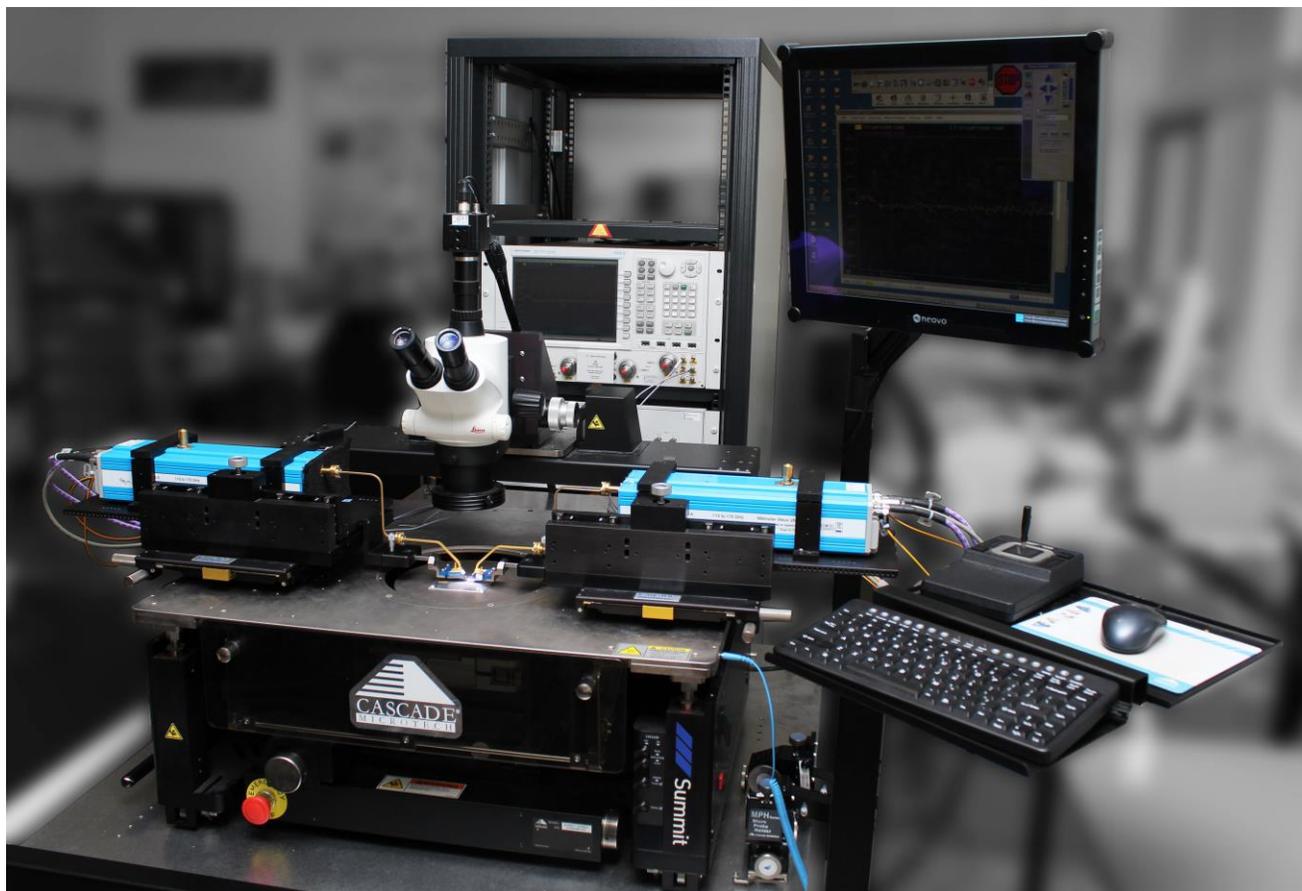


# 在片测量

在片测试系统：非常精确，尤其在高频测量中



# 在片测量系统



网络分析仪

控制电脑

显微镜

扩展模块

探针台

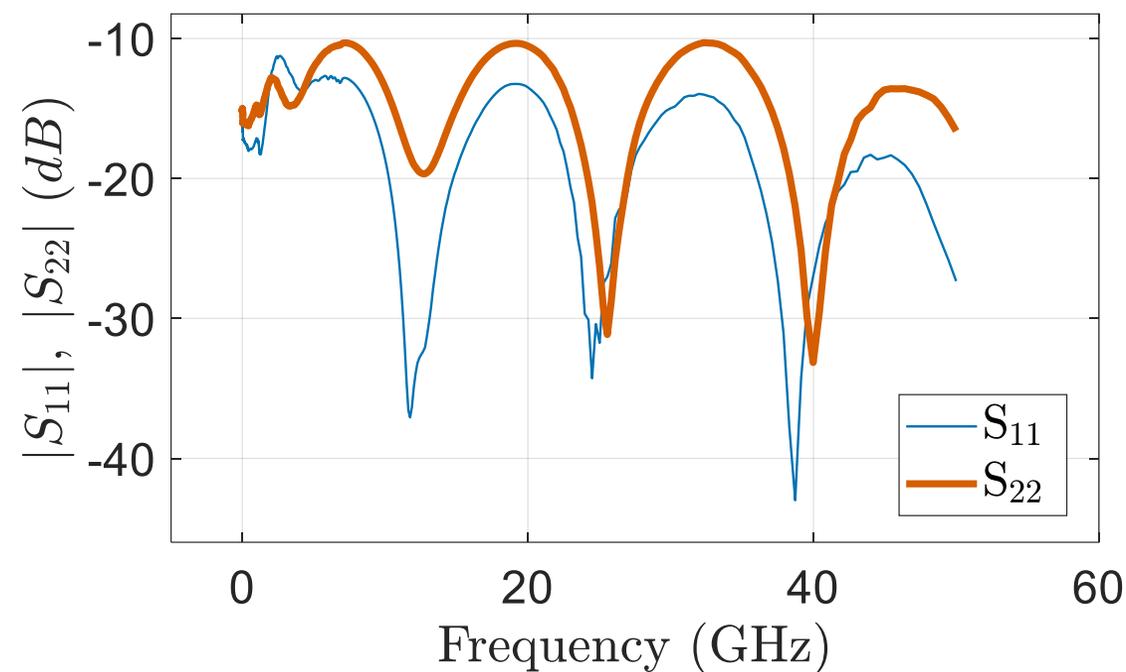
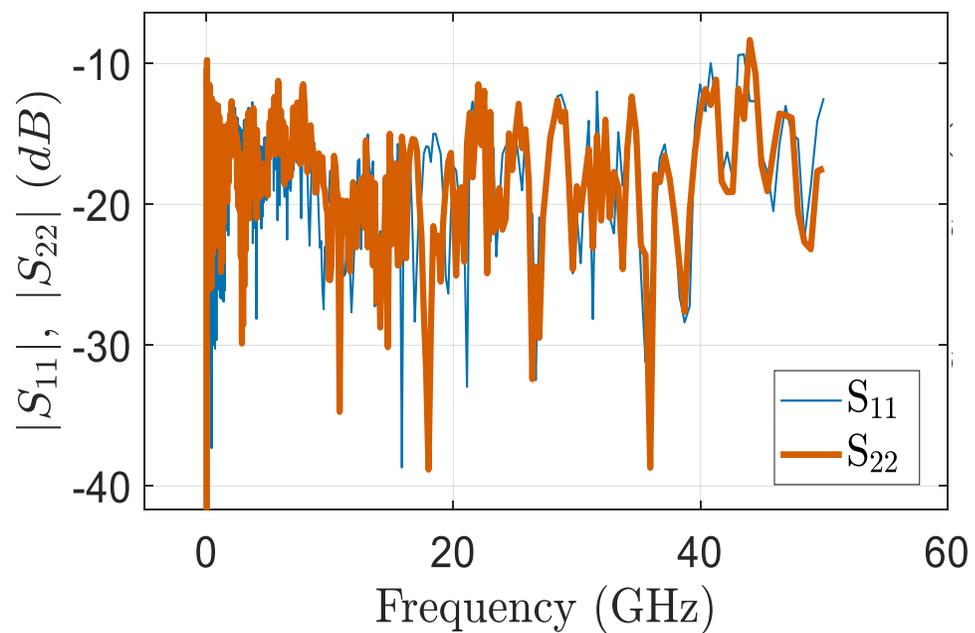
探针



cascade

GGB

# 校准的意义

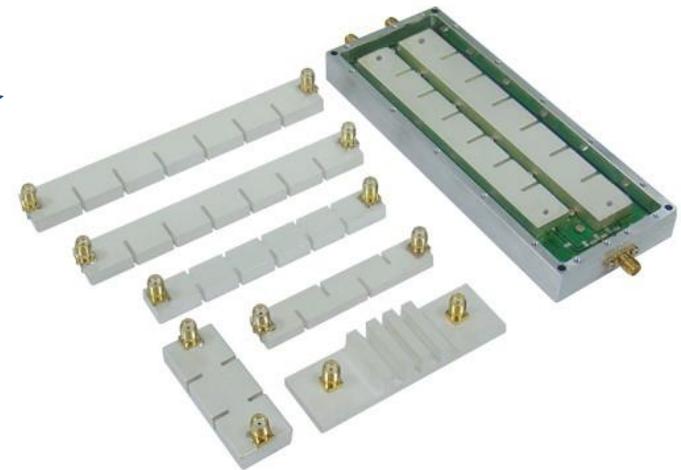


我们感兴趣的信号能够准确地传输。。。

# 信号传输？



频率?!



# 常用的低频件



# 同轴线 (50欧姆)

$$C' = \frac{2\pi\epsilon_0\epsilon_R}{\ln(D/d)} \text{ (Farads/meter)}$$

where :

$$\epsilon_0 = 8.854 \times 10^{-12} \text{ Farads/meter}$$

$$L' = \frac{\mu_0\mu_R}{2\pi} \ln(D/d) \text{ (Henries/meter)}$$

where :

$$\mu_0 = 4\pi \times 10^{-7} \text{ (Henries/meter)}$$

$$Z_0 = \sqrt{\frac{L'}{C'}} = \frac{1}{2\pi} \sqrt{\frac{\mu_0\mu_R}{\epsilon_0\epsilon_R} \ln(D/d)} \text{ (Ohms)}$$

$$\text{Loss/length} = 8.686 \times \frac{\text{Resistance/length}}{2Z_0}$$

$$\text{Loss/length} = \frac{8.686}{2 \times 138} \left( \frac{f\mu_0\epsilon_R}{\pi} \right)^{\frac{1}{2}} \times \left( \frac{(\mu_{R1}\rho_1)^{\frac{1}{2}}}{D} + \frac{(\mu_{R2}\rho_2)^{\frac{1}{2}}}{d} \right) \times \frac{1}{\log(D/d)}$$

units are dB/length

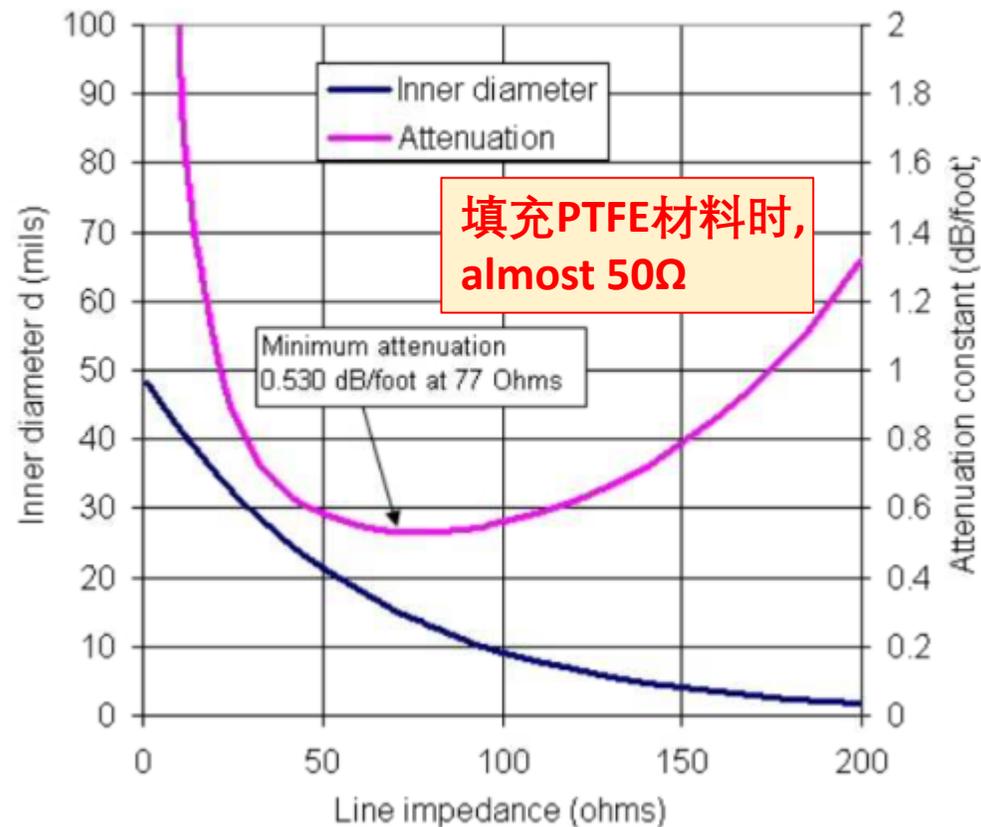
where:

$\mu_{R1}$  and  $\rho_1$  are properties of outside conductor

$\mu_{R2}$  and  $\rho_2$  are properties of inside conductor

导体电阻损耗

Air coax metal loss, copper conductors, D=49 mils  
ER=1, rho=1.67 u-ohm-cm, F=10 GHz



# 同轴线频率

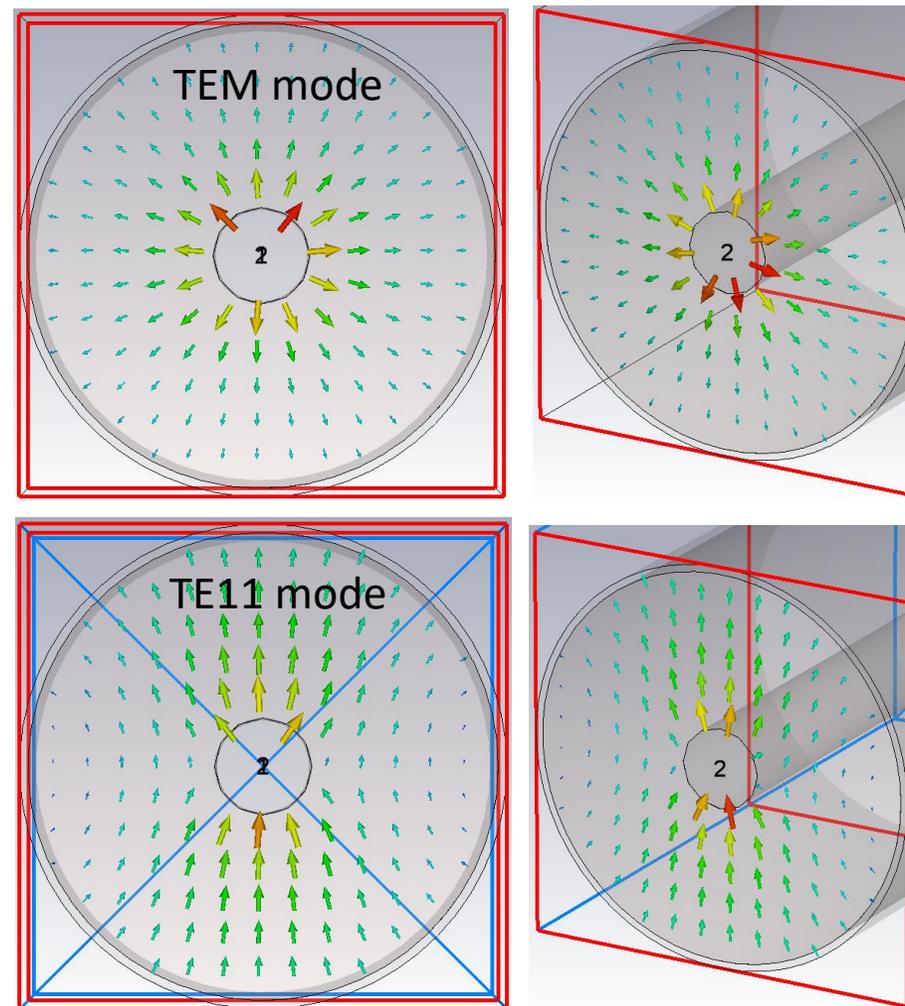
截止频率：当电磁能量波长的大小超过横向电磁（TEM）模式并开始沿同轴线“反弹”为横向电模式（TE<sub>11</sub>）时，会产生同轴电缆截止频率（上限频率）。新频率模式与TEM模式传播速度不同，会对TEM模式信号产生反射和干扰。

介质中间处周长应小于  $\lambda_{\text{eff}}$ ：

$$\lambda_c = \pi \left( \frac{D+d}{2} \right) \sqrt{\mu_r \epsilon_r}$$
$$f_c = \frac{c}{\lambda_c} = \frac{c}{\pi \left( \frac{D+d}{2} \right) \sqrt{\mu_r \epsilon_r}}$$

(新的mode) **Why? How?**

集肤深度，损耗，阻抗变化等？



# 同轴线连接器转接头

SMA连接器、3.5mm、2.92mm、2.4mm、1.85mm、1mm连接器 (参数一般为外导体内径)

SMA: ~18GHz(接半硬电缆), ~12.4GHz(接软电缆)  
聚四氟乙烯(PTFE)介质填充

3.5mm: ~33GHz  
空气介质

2.92mm: ~46GHz

2.4mm: ~50GHz

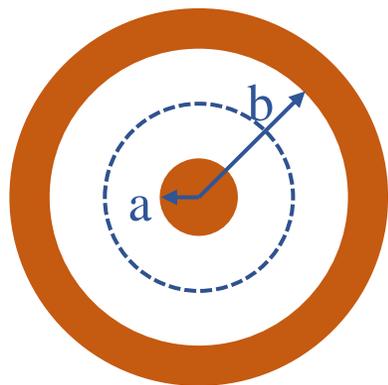
1.85mm: ~67GHz

1mm: ~110Gz

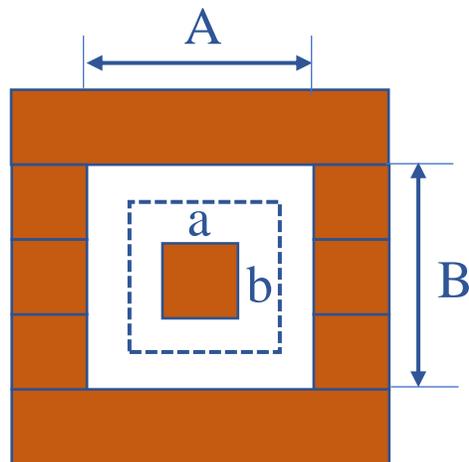
(可互连)



# 更小尺寸？微同轴？



$$\text{周长} l = 2\pi\left(\frac{a+b}{2}\right)$$

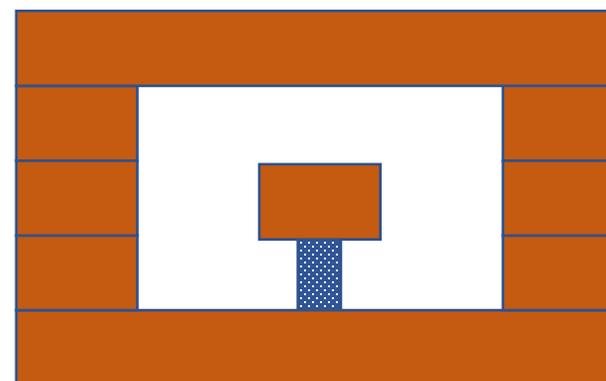
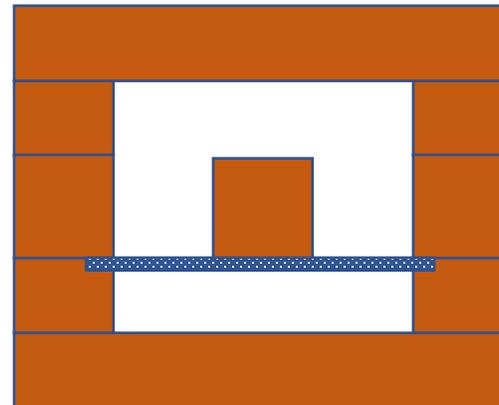


$$\text{周长} l = 2\left(\frac{A+a}{2} + \frac{B+b}{2}\right)$$

矩形同轴估算：

$$\lambda_c = l\sqrt{\mu_r\epsilon_r}$$

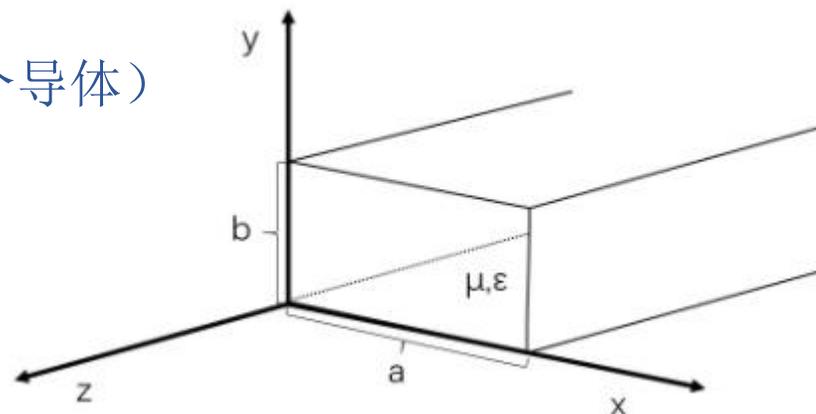
$$f_c = \frac{c}{\lambda_c} = \frac{c}{l\sqrt{\mu_r\epsilon_r}}$$



# 矩形波导

传输线可以分为两大类：单导体和多导体（至少2个导体）

矩形波导(常见TE<sub>10</sub>)工作频率：  
在125% 到 189% 的截止频率



TE<sub>m</sub>n和TM<sub>m</sub>n的截止波数:

$$K_c = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$$

截止频率:

$$f_c = \frac{v}{\lambda_c} = \frac{vK_c}{2\pi} = \frac{\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}}{2\sqrt{\mu\epsilon}}$$



# 矩形波导



波导类型	频率范围	波导口宽度(um)	截止频率 (GHz)	
			1.25 fc	1.9 fc
WR 10	75-110GHz	2540	59.01426339	73.76782923
WR 8	90-140GHz	2032	73.76782923	92.20978654
WR 6	110-170GHz	1651	90.79117444	113.488968
WR 5	140-220GHz	1295	115.7499838	144.6874797
WR 4	170-260GHz	1092	137.267609	171.5845112
WR 3	220-325GHz	864	173.4910058	216.8637572
WR 2.8	260-400GHz	710	211.1214493	263.9018116
WR 2.2	330-500GHz	570	262.9758404	328.7198004
WR 1.9	400-600GHz	470	318.9281468	398.6601835
WR 1.5	500-750GHz	380	394.4637605	493.0797007
WR 1.2	600-900GHz	310	483.5362226	604.4202782
WR 1.0	750-1100GHz	250	599.584916	749.481145
WR 0.80	900-1400GHz	200	749.481145	936.8514313
WR 0.65	1100-1700GHz	164	914.0013963	1142.501745
WR 0.51	1400-2200GHz	130	1153.047915	1441.309894
WR 0.43	1700-2600GHz	106	1414.115368	1767.64421
WR 0.34	2200-3300GHz	86	1742.979407	2178.724259
WR 0.28	2600-4000GHz	70	2141.3747	2676.718375
WR 0.22	3300-5000GHz	58	2584.417741	3230.522177

国标型号 | 国际标型号 | 频率范围GHz | 截面尺寸(宽)(高)

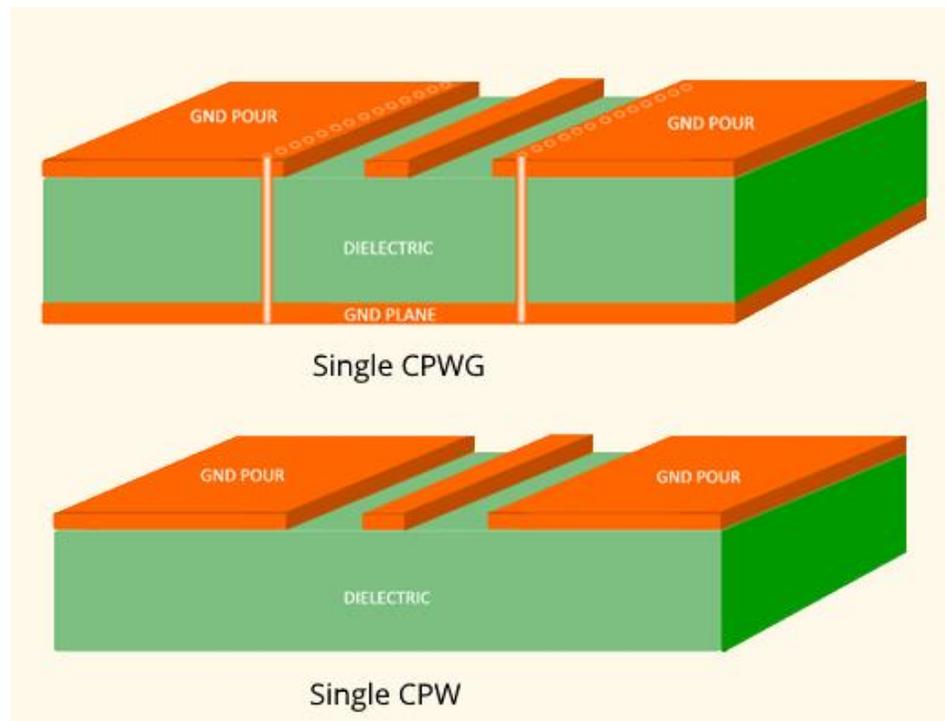
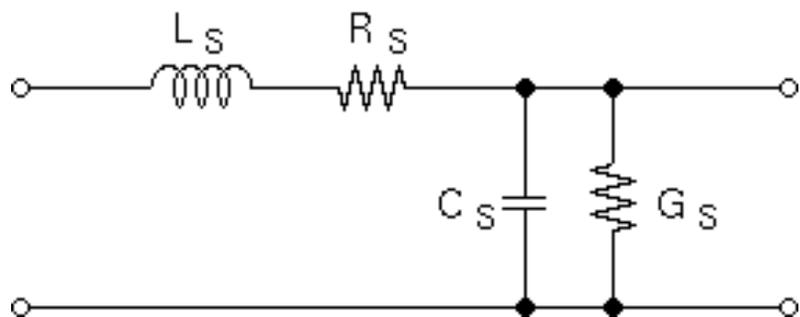
BJ14	WR650	1.13~1.73	165.1	82.55
BJ18	WR510	1.45~2.20	129.54	64.77
BJ22	WR430	1.72~2.61	109.22	54.61
BJ26	WR340	2.17~3.30	86.36	43.18
BJ32	WR284	2.60~3.95	72.14	34.04
BJ40	WR229	3.22~4.90	58.17	29.08
BJ48	WR187	3.94~5.99	47.549	22.149
BJ58	WR159	4.64~7.05	40.386	20.193
BJ70	WR137	5.38~8.17	34.849	15.799
BJ84	WR112	6.57~9.99	28.499	12.624
BJ100	WR90	8.20~12.5	22.86	10.16
BJ120	WR75	9.84~15.0	19.05	9.525
BJ140	WR62	11.9~18.0	15.799	7.899
BJ180	WR51	14.5~22.0	12.954	6.477
BJ220	WR42	17.6~26.7	10.668	4.318
BJ260	WR34	21.7~33.0	8.636	4.318
BJ320	WR28	26.3~40.0	7.112	3.556
BJ400	WR22	32.9~50.1	5.69	2.845
BJ500	WR18	39.2~59.6	4.775	2.388
BJ620	WR14	49.8~75.8	3.759	1.88
BJ740	WR12	60.5~91.9	3.0988	1.5494
BJ900	WR10	73.8~112	2.54	1.27

# 矩形波导

直波导	转接波导	扭波导	弯波导	软波导
				
喇叭天线	E/H 调谐器	耦合器	可调短路器	旋转关节
				
滤波器	负载	衰减器	检波器	混频器
				

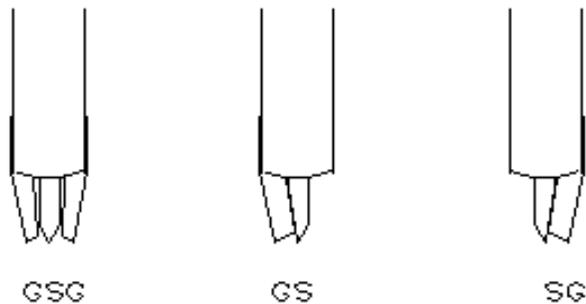
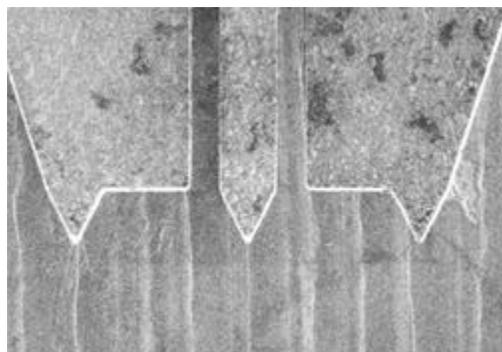
# 共面波导

- TEM mode;
- $E_{eff} = \epsilon_r/2 + 1/2$ ;
- 容易加工;
- 工作频率很高

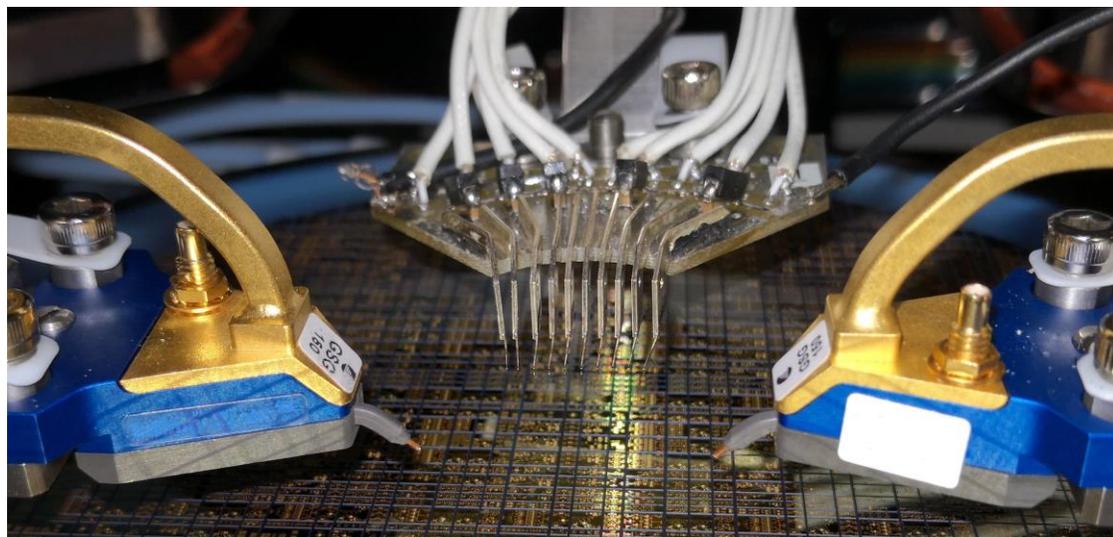


# 转换头： 探针

Top View



GSG, SG, GS, GSGSG, GSSG, SGS等



液晶 (LCP), 镀镍, 非氧化镍合金

# 双端口网络模型

## 模型考虑因素

- 网络分析仪原理结构
- 端口之间的串扰

## 常用误差模型

- 10（12）相误差模型
- 7（8）相误差模型
- 15（16）相误差模型

# 误差模型

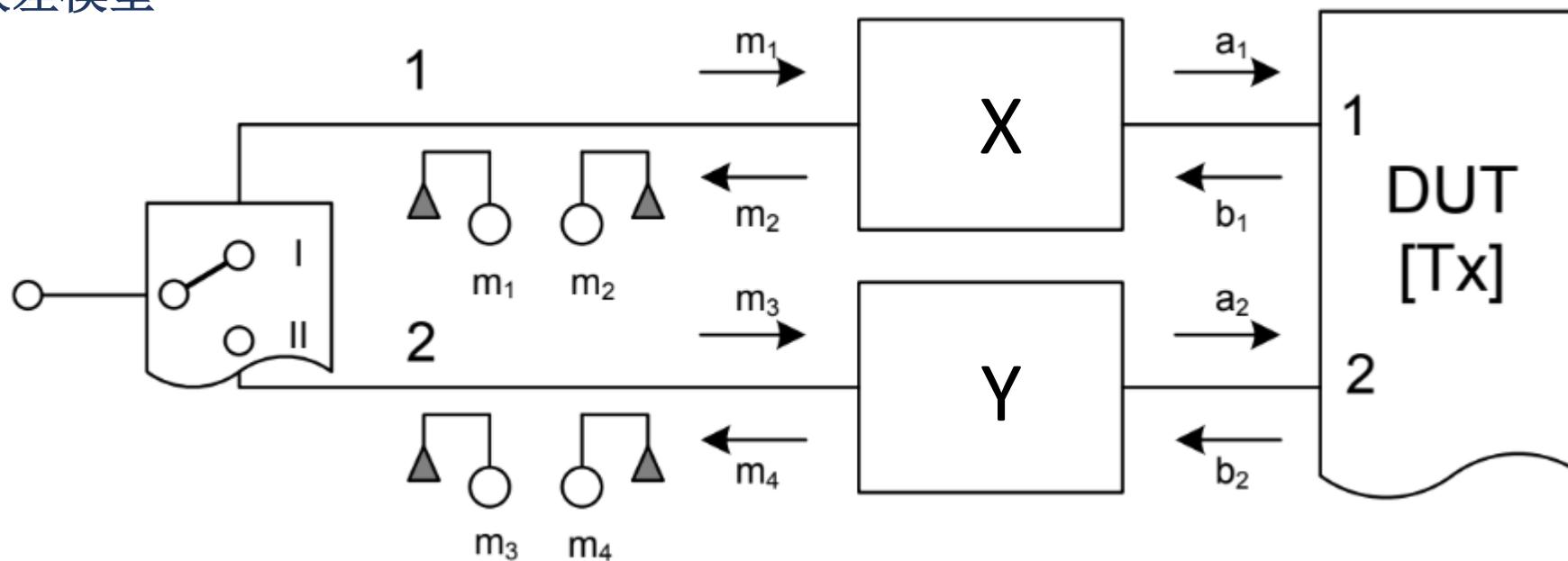
误差模型考虑因素：

- VNA 的端口数和测量接收机的数量
- 测量精度要求（串扰等）

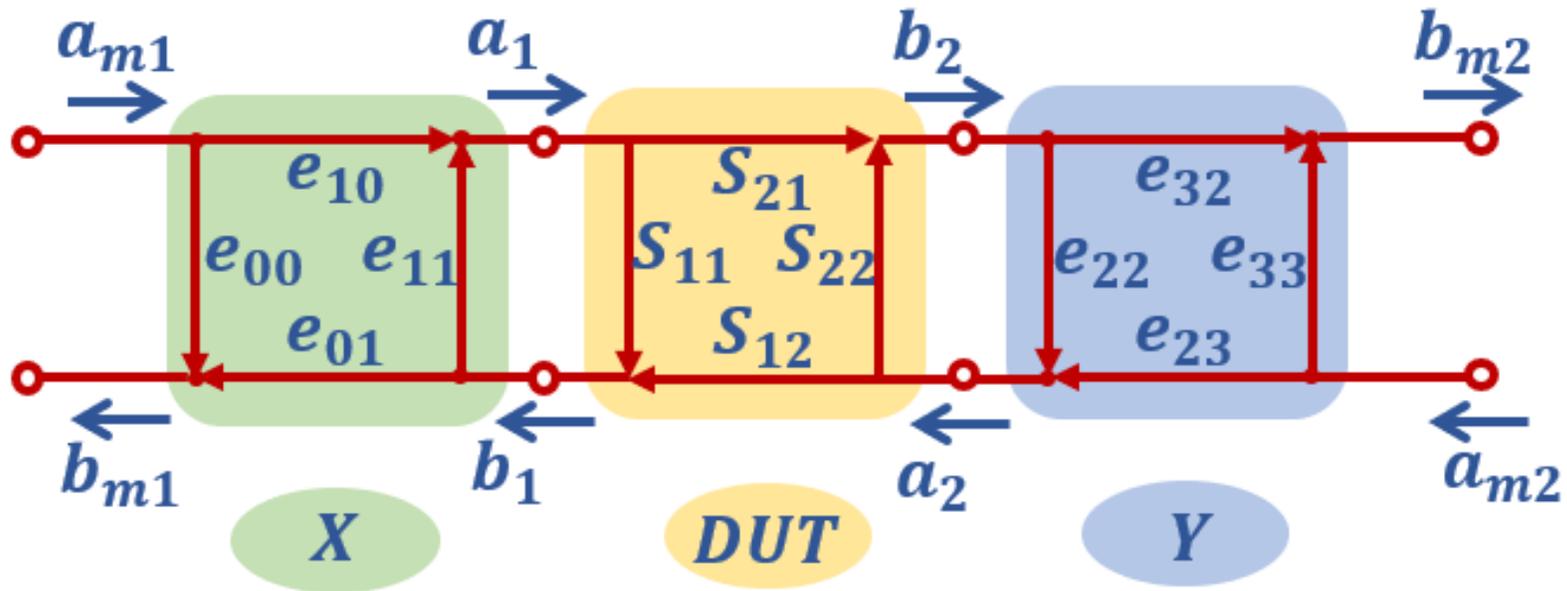
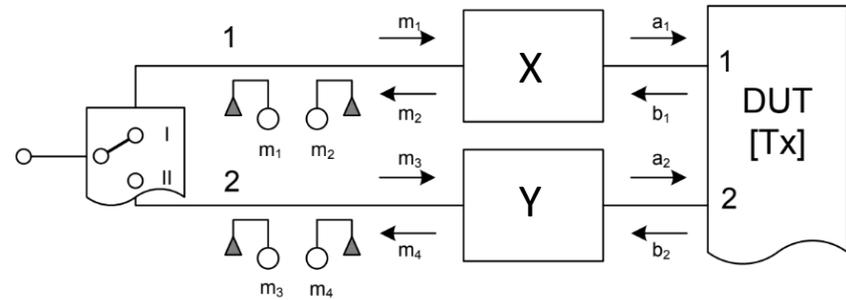
# 8相误差模型

基于双-反射计结构的VNA:

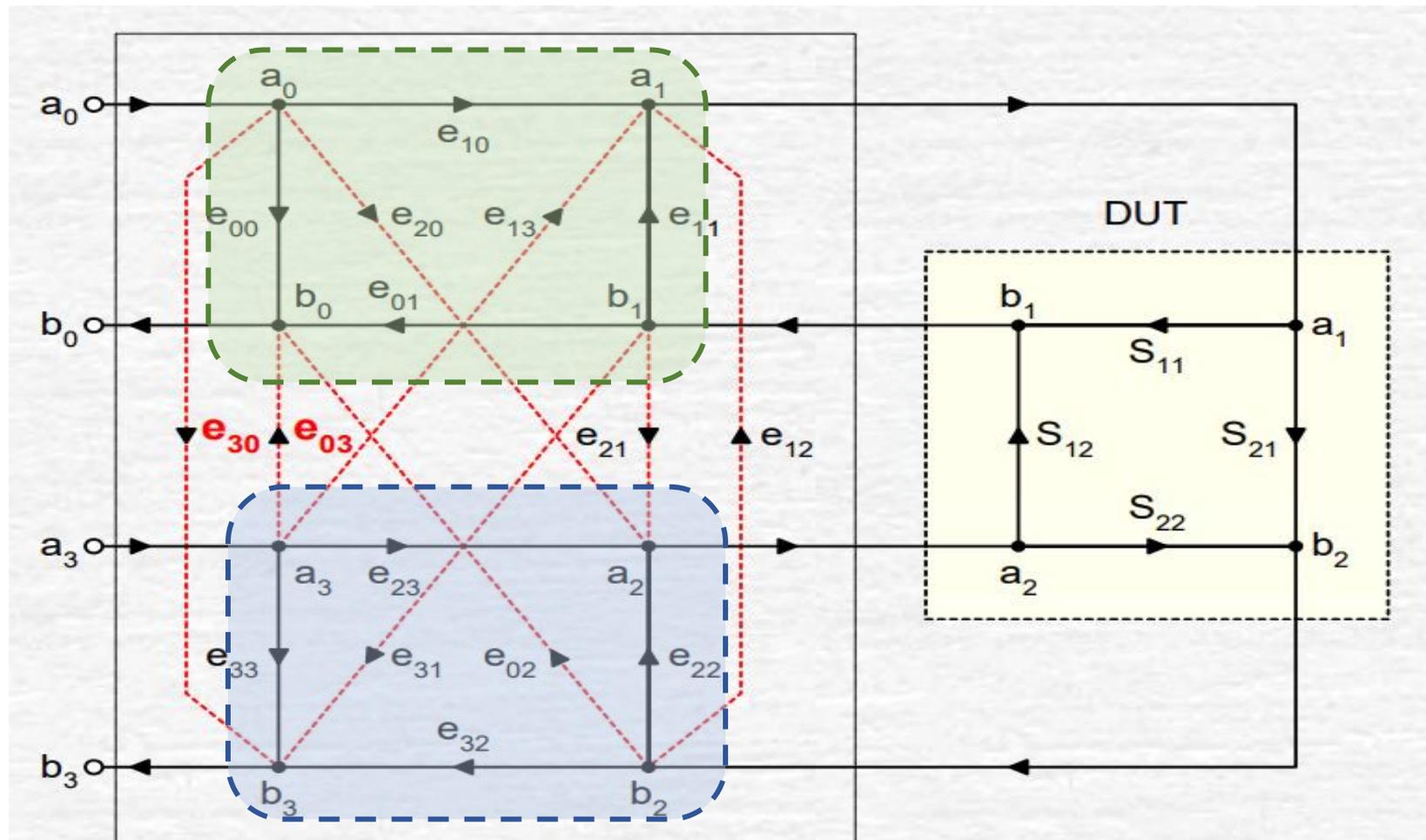
- 每个port对应2个接收机
- 10相或16相误差模型
- 8相误差模型



# 8相误差模型



# 16 (15) 相误差模型



若只考虑 $e_{03}$ 和 $e_{30}$ ,  
是10相误差模型

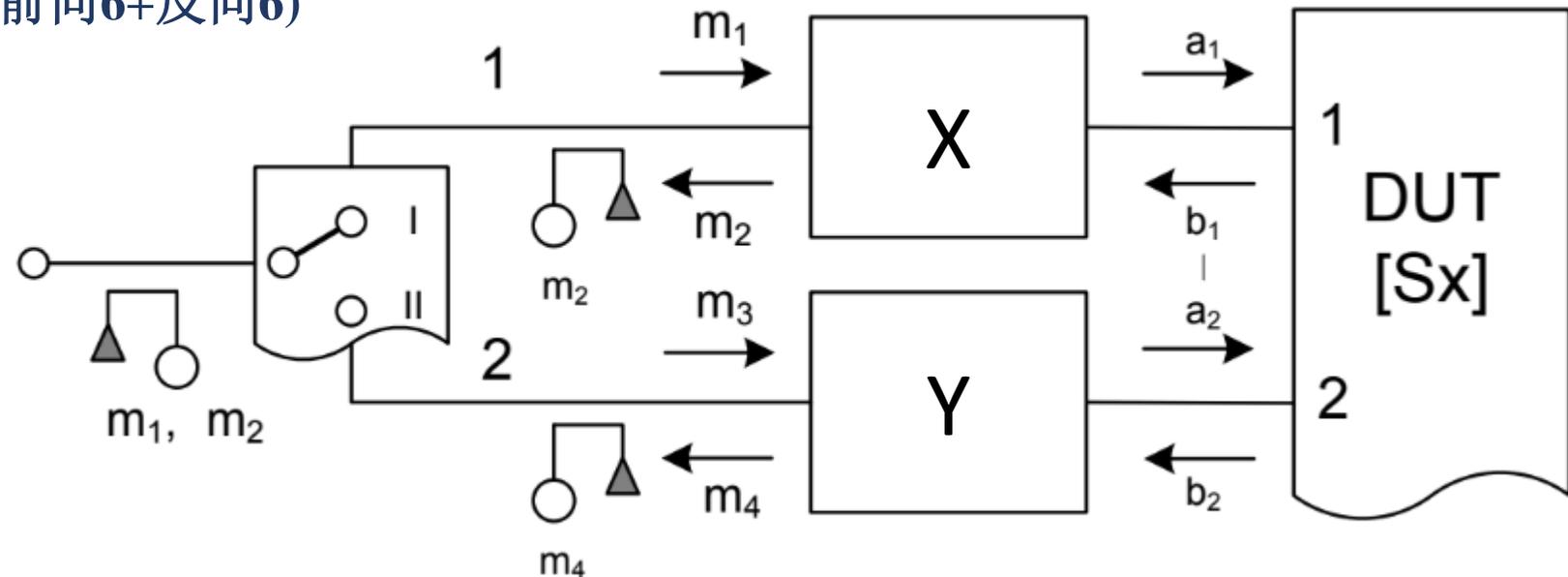
$e_{00}, e_{33}$  Directivity  
 $e_{11}, e_{22}$  Port Match  
 $e_{10}, e_{01}, e_{32}, e_{23}$  Tracking  
 $e_{30}, e_{03}$  Primary Leakage

All others are lower level leakage paths

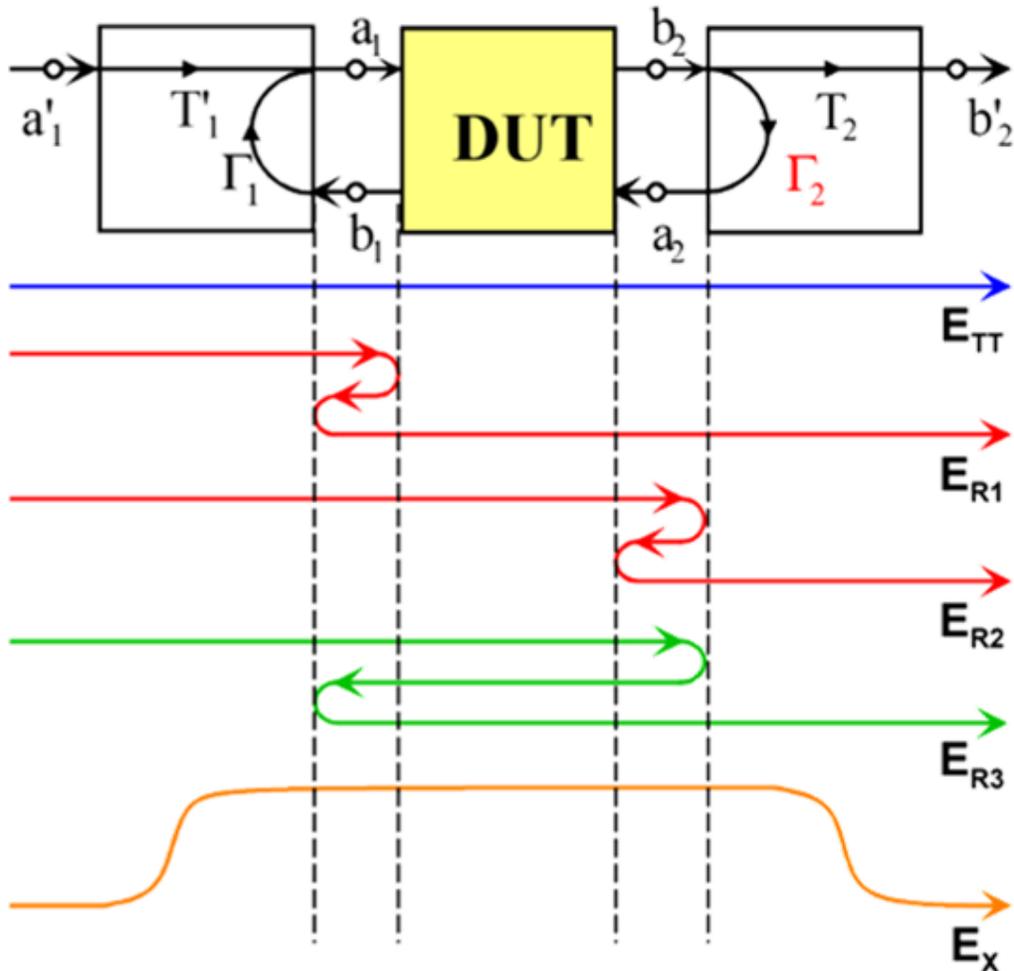
# 12相误差模型

基于参考信道的VNA:

- 所有测量port共享1个(入射信号)接收机
- 所有port额外有1个测量接收机
- 10相误差模型(前向6+反向6)



# 12相误差模型



1. Forward Transmission Loss

$E_{TT}$

2. Mismatch-reflections DUT / Port 1

$E_{R1}$

3. Mismatch-reflections DUT / Port 2

$E_{R2}$

4. Multiport mismatch-reflections

$E_{R3}$

5. Crosstalk

$E_X$

# 12相误差模型

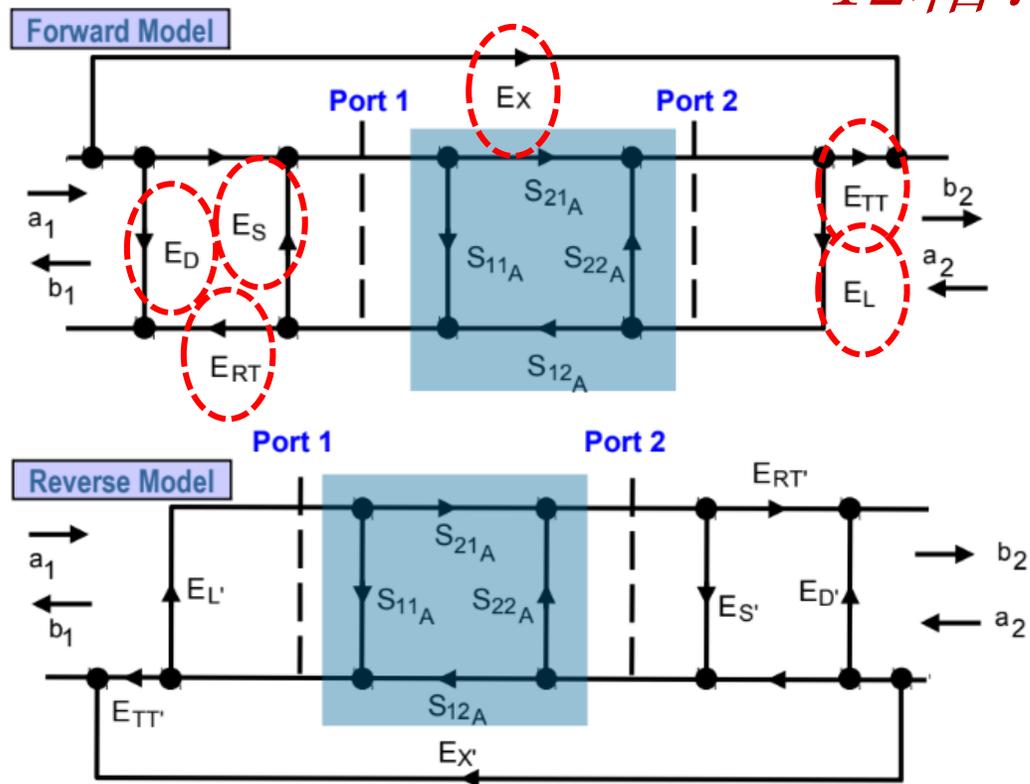
12相!

$$S_{11a} = \frac{\left(\frac{S_{11m} - E_D}{E_{RT}}\right)\left(1 + \frac{S_{22m} - E_{D'}}{E_{RT'}} E_{S'}\right) - E_L \left(\frac{S_{21m} - E_X}{E_{TT}}\right) \left(\frac{S_{12m} - E_{X'}}{E_{TT'}}\right)}{\left(1 + \frac{S_{11m} - E_{D'}}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_{D'}}{E_{RT'}} E_{S'}\right) - E_L' E_L \left(\frac{S_{21m} - E_X}{E_{TT}}\right) \left(\frac{S_{12m} - E_{X'}}{E_{TT'}}\right)}$$

$$S_{21a} = \frac{\left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(1 + \frac{S_{22m} - E_{D'}}{E_{RT'}} (E_{S'} - E_L)\right)}{\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_{D'}}{E_{RT'}} E_{S'}\right) - E_L' E_L \left(\frac{S_{21m} - E_X}{E_{TT}}\right) \left(\frac{S_{12m} - E_{X'}}{E_{TT'}}\right)}$$

$$S_{12a} = \frac{\left(\frac{S_{12m} - E_{X'}}{E_{TT'}}\right)\left(1 + \frac{S_{11m} - E_D}{E_{RT}} (E_S - E_L')\right)}{\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_{D'}}{E_{RT'}} E_{S'}\right) - E_L' E_L \left(\frac{S_{21m} - E_X}{E_{TT}}\right) \left(\frac{S_{12m} - E_{X'}}{E_{TT'}}\right)}$$

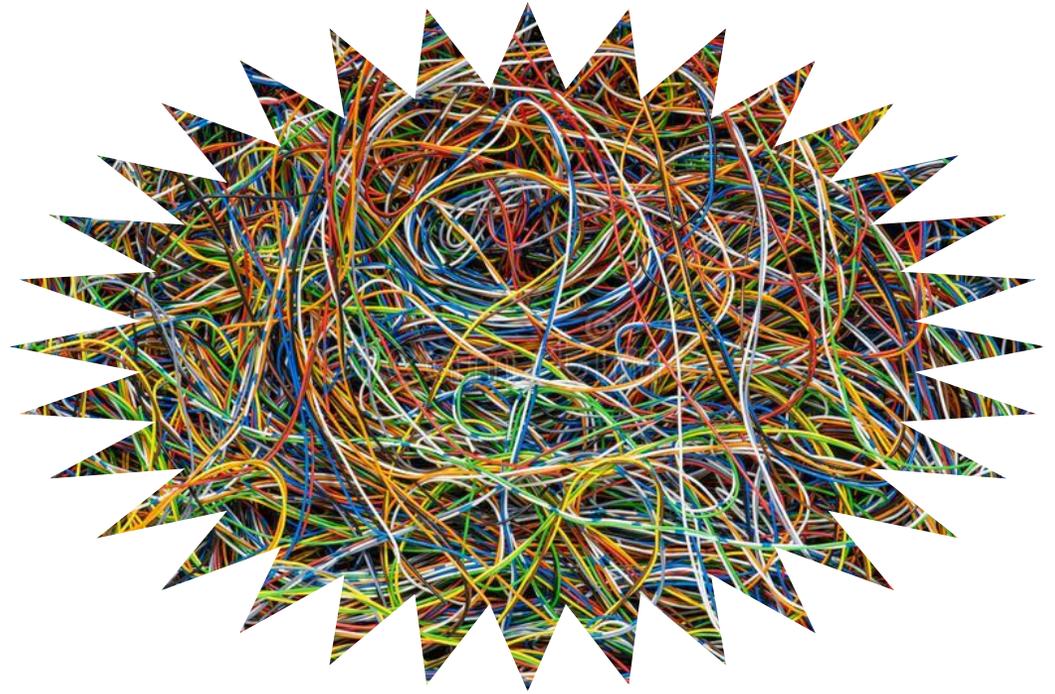
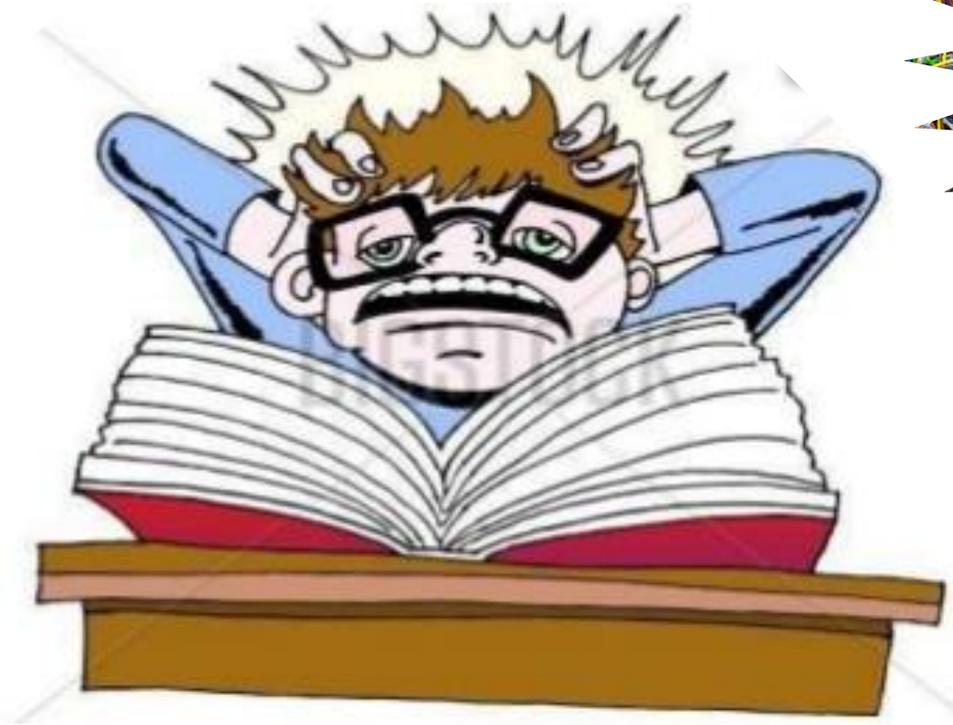
$$S_{22a} = \frac{\left(\frac{S_{22m} - E_{D'}}{E_{RT'}}\right)\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right) - E_L' \left(\frac{S_{21m} - E_X}{E_{TT}}\right) \left(\frac{S_{12m} - E_{X'}}{E_{TT'}}\right)}{\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_{D'}}{E_{RT'}} E_{S'}\right) - E_L' E_L \left(\frac{S_{21m} - E_X}{E_{TT}}\right) \left(\frac{S_{12m} - E_{X'}}{E_{TT'}}\right)}$$



- |                                     |                                       |
|-------------------------------------|---------------------------------------|
| $E_D$ = fwd directivity             | $E_L$ = fwd load match                |
| $E_S$ = fwd source match            | $E_{TT}$ = fwd transmission tracking  |
| $E_{RT}$ = fwd reflection tracking  | $E_X$ = fwd isolation                 |
| $E_{D'}$ = rev directivity          | $E_{L'}$ = rev load match             |
| $E_{S'}$ = rev source match         | $E_{TT'}$ = rev transmission tracking |
| $E_{RT'}$ = rev reflection tracking | $E_{X'}$ = rev isolation              |

4个校准后的S参数是测量S参数的函数

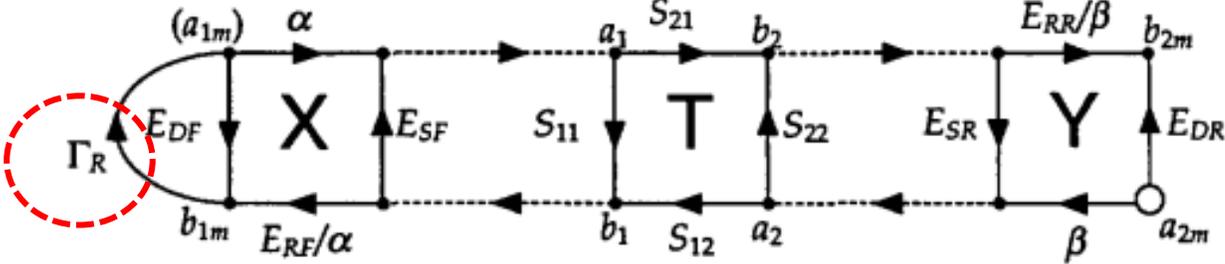
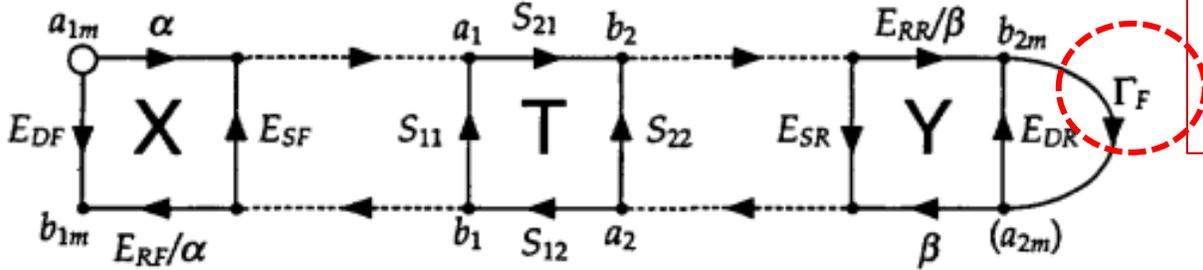
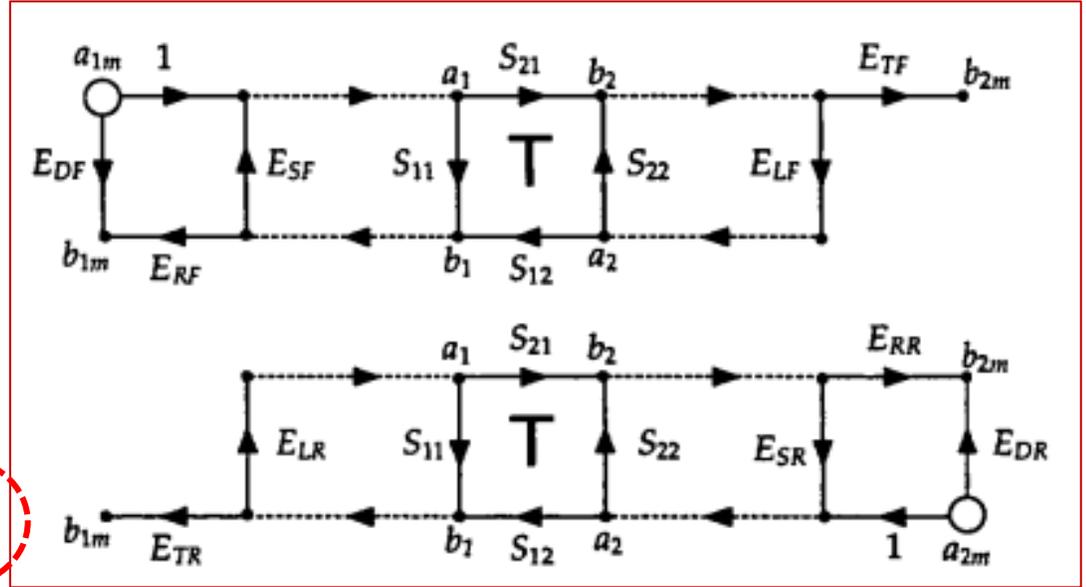
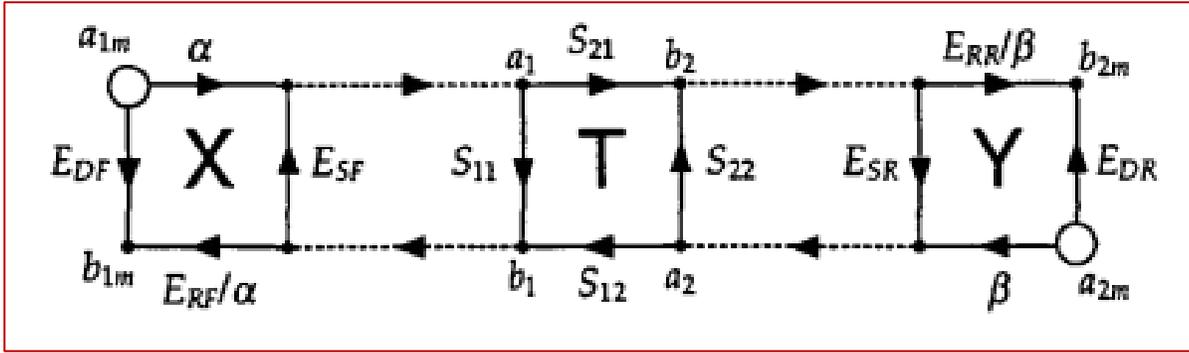
# 如何简化？



# 12相与8相误差模型间的联系

8相

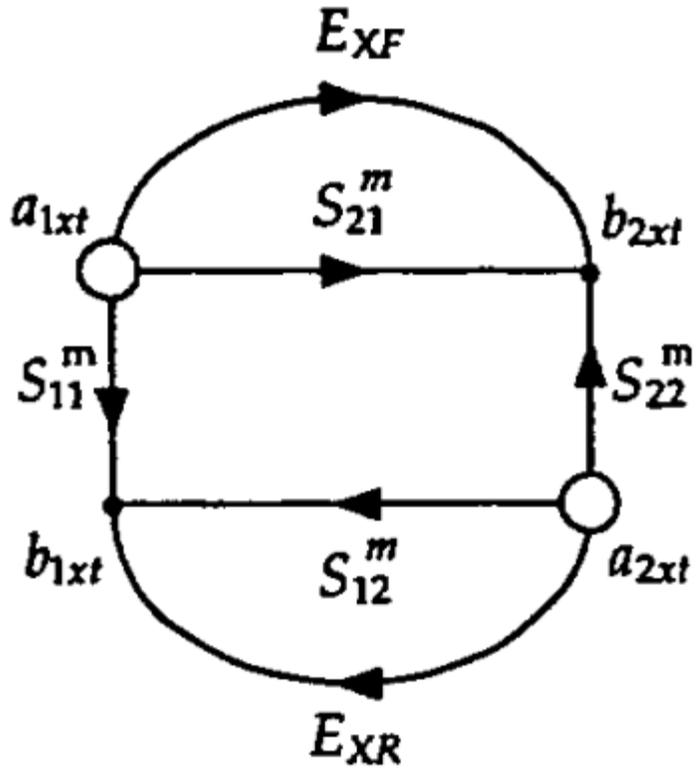
10相



$\Gamma_F$ 和 $\Gamma_R$ :  
switch terms

Switch terms  
仅与内部端口  
有关，和线连  
接等导致的  
error box无关

# 串扰 (Ex)

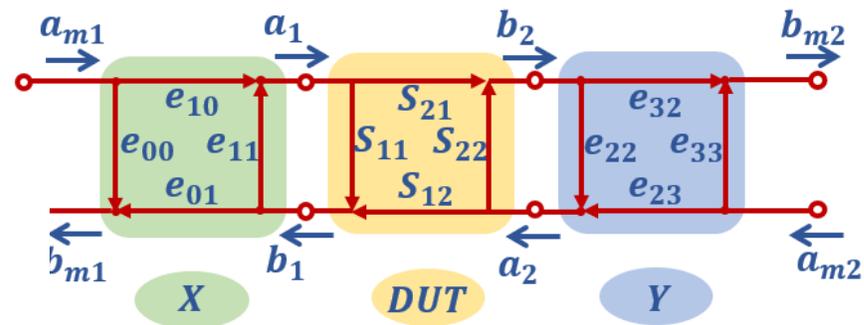
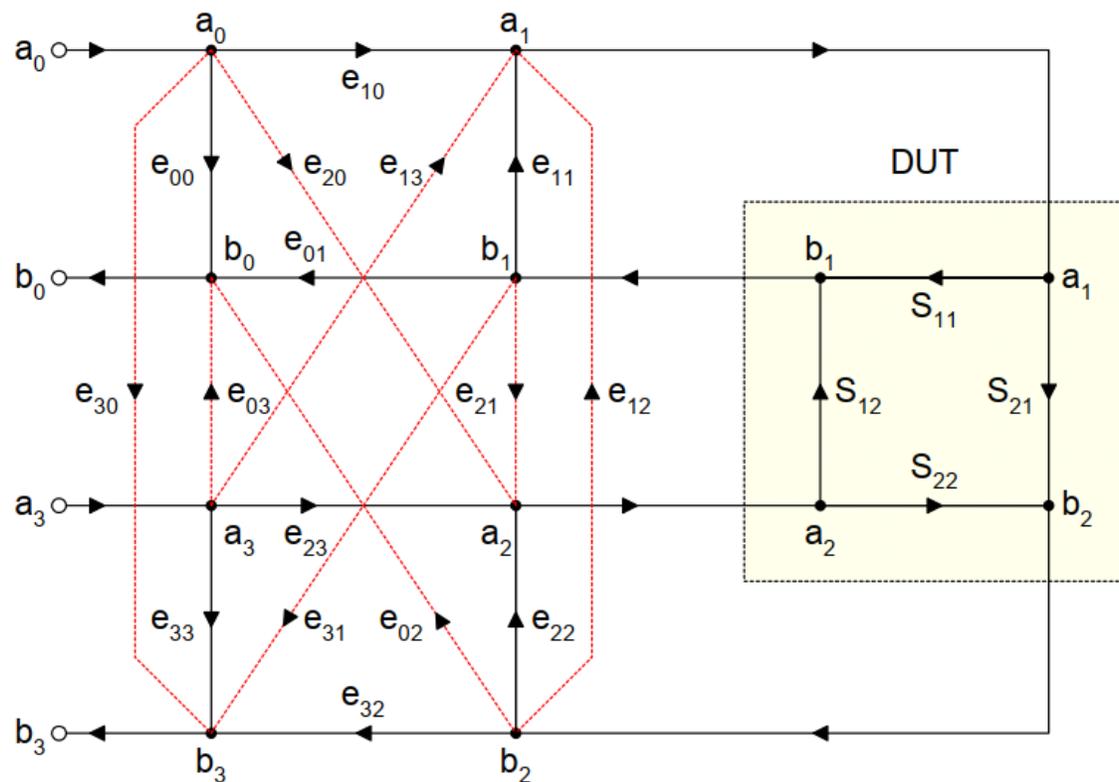


Crosstalk 模型

串扰不在误差模型里考虑。。

$$S_{21}^m = S_{21}^{xt} - E_{XF}, \text{ where } S_{21}^{xt} \equiv \frac{b_{2xt}}{a_{1xt}}$$
$$S_{12}^m = S_{12}^{xt} - E_{XR}, \text{ where } S_{12}^{xt} \equiv \frac{b_{1xt}}{a_{2xt}}.$$

# 16相与8相误差模型间的联系



一般用T和S参数矩阵计算

$$\begin{bmatrix} b_0 \\ b_3 \\ a_0 \\ a_3 \end{bmatrix} = \begin{bmatrix} T_1 & T_2 \\ T_3 & T_4 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ a_1 \\ a_2 \end{bmatrix}$$

# 8相误差模型简化

8相模型变7相模型

$$T = \frac{1}{S_{21}} \begin{bmatrix} \Delta S & S_{11} \\ -S_{22} & 1 \end{bmatrix}$$

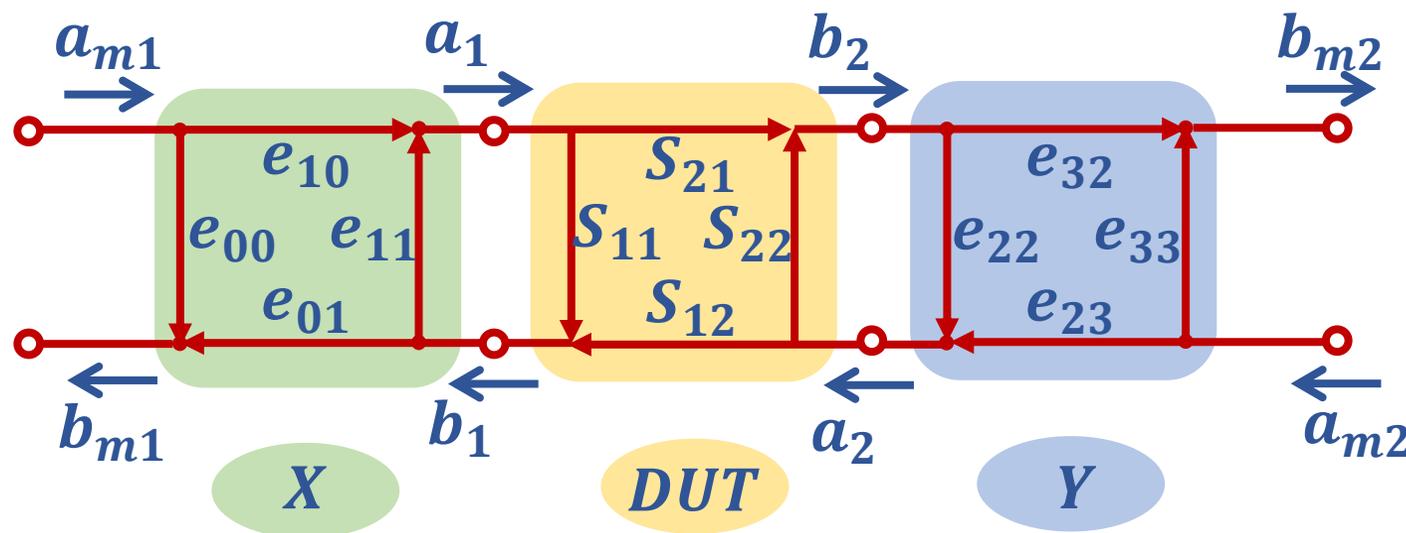
$$\Delta S = S_{12}S_{21} - S_{11}S_{22}$$



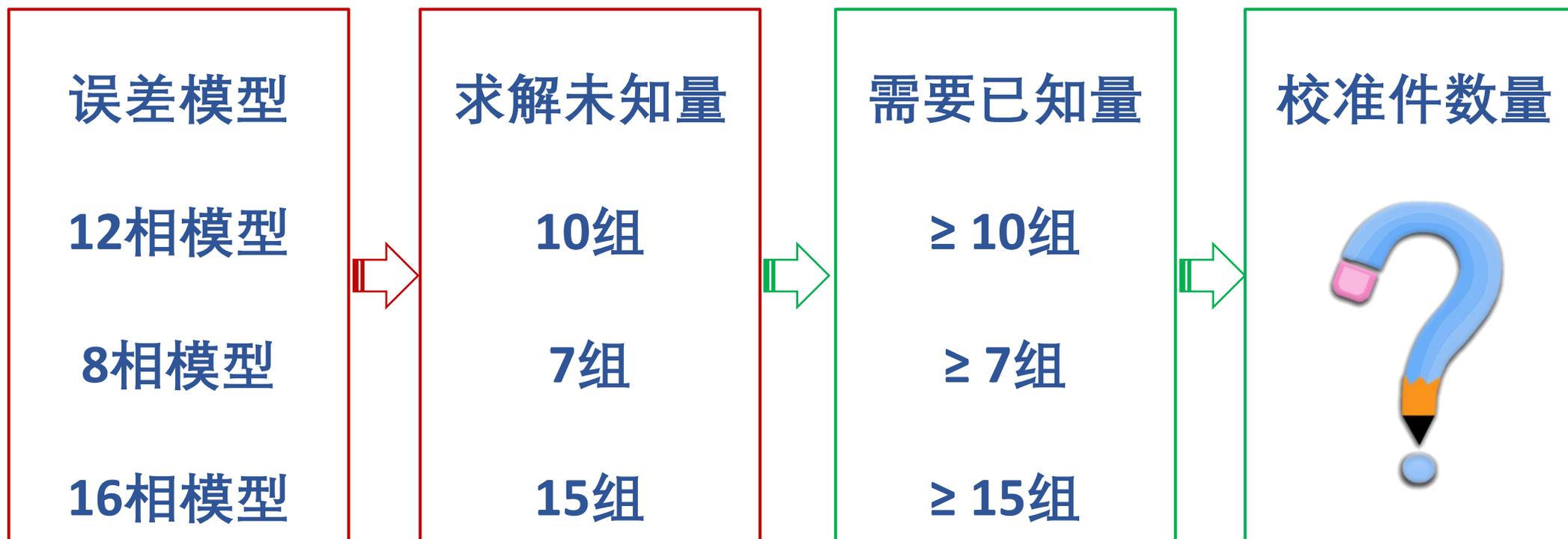
$$T_m = T_X T_{DUT} T_Y^{-1}$$

$$T_m = \frac{1}{S_{21X}S_{12Y}} \begin{bmatrix} \Delta S_X & S_{11X} \\ -S_{22X} & 1 \end{bmatrix} T_{DUT} \begin{bmatrix} \Delta S_Y & S_{22Y} \\ -S_{11Y} & 1 \end{bmatrix}$$

7相!

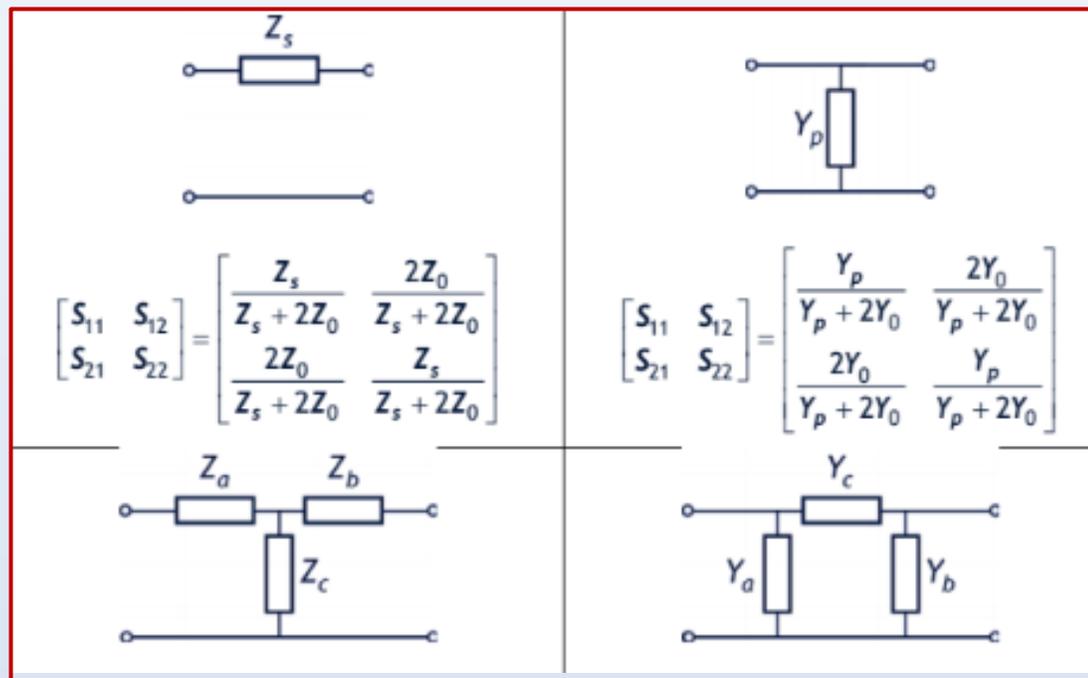


# 误差模型与校准件数量？

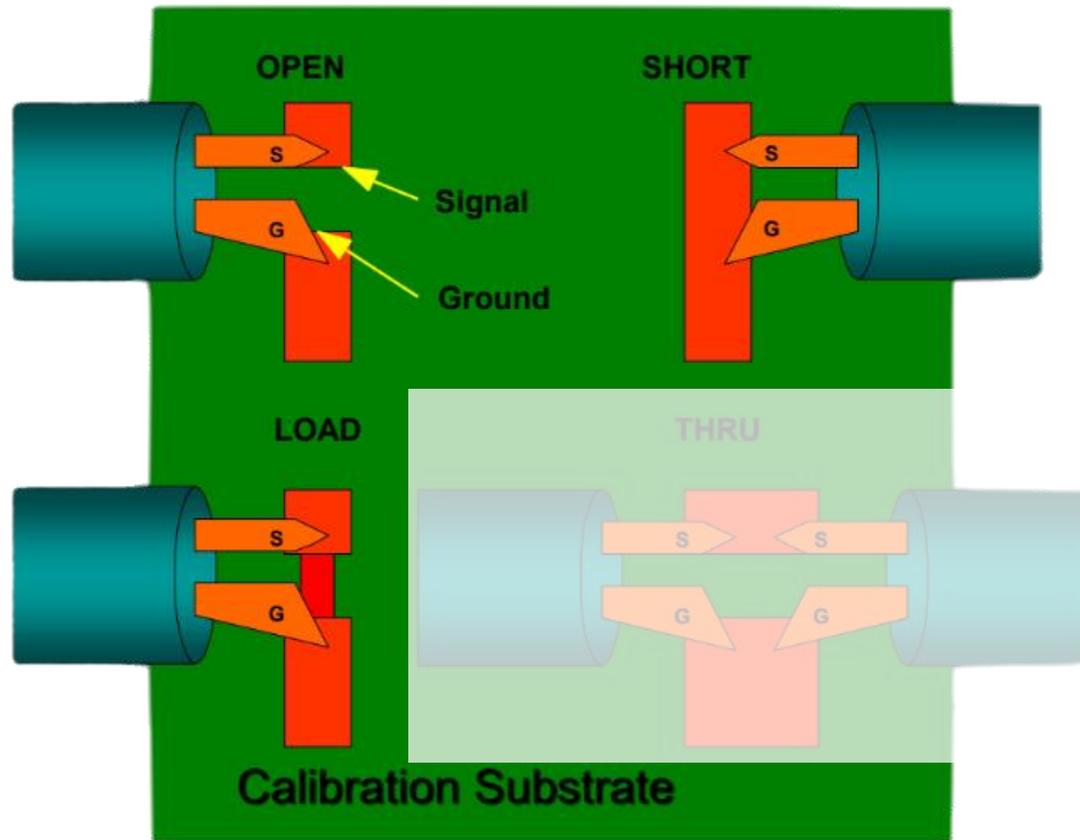


# 校准件选择?

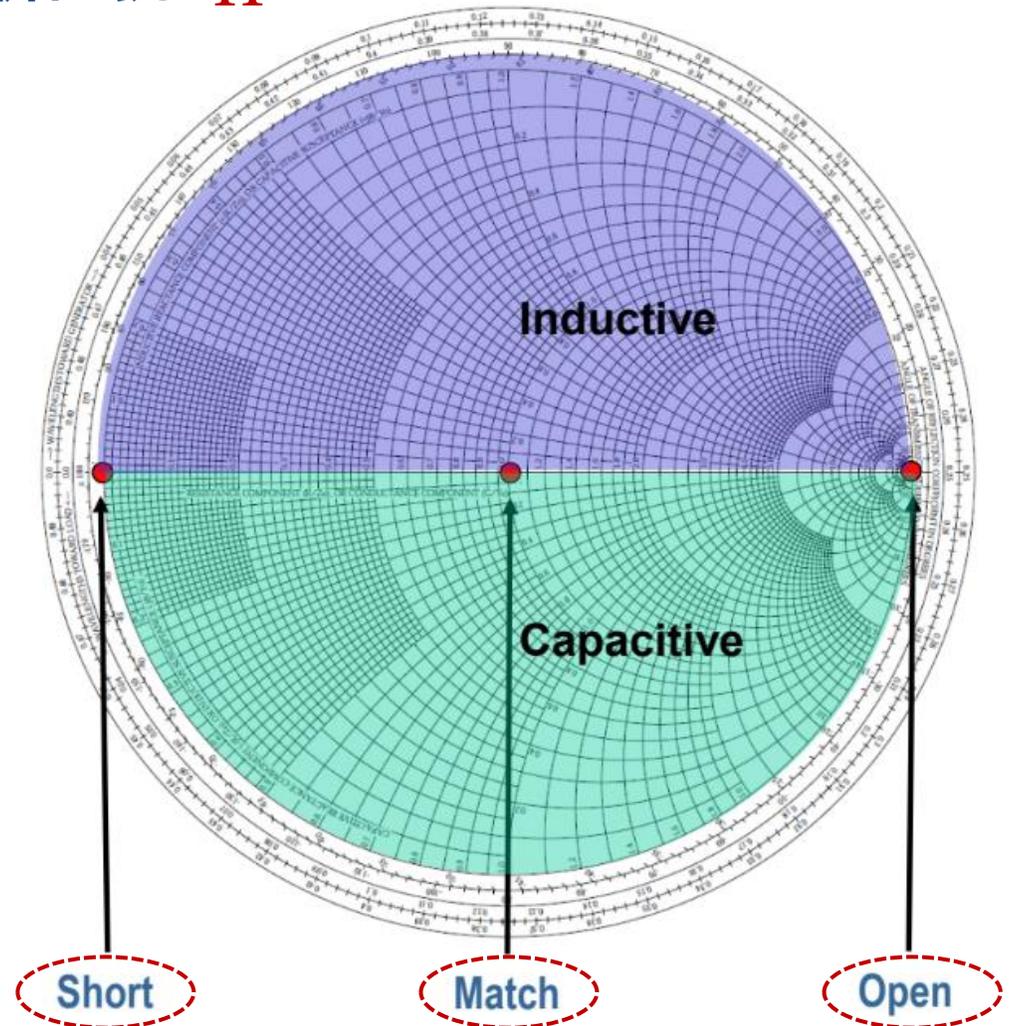
- Thru 通路
- Open 开路
- Short 短路
- Load 并联电阻
- Series resistor 串联电阻
- Line 传输线



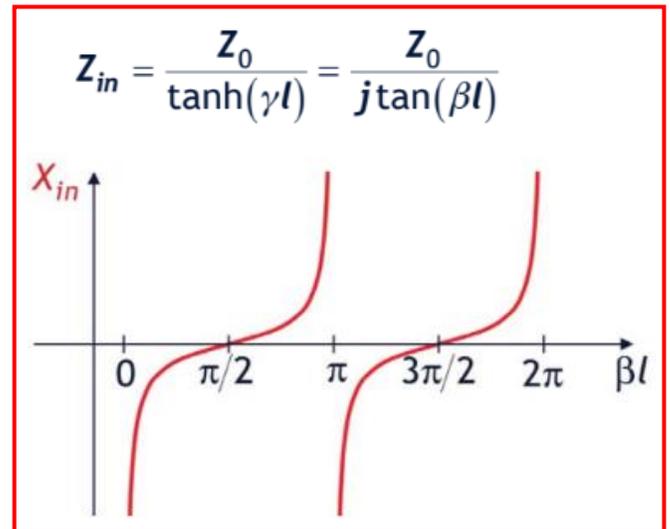
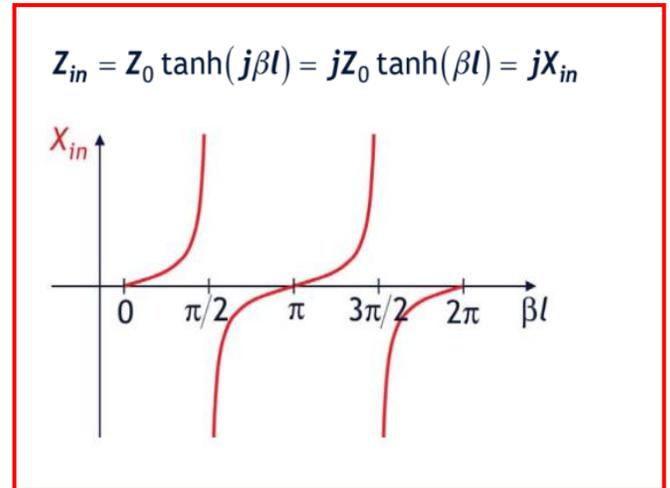
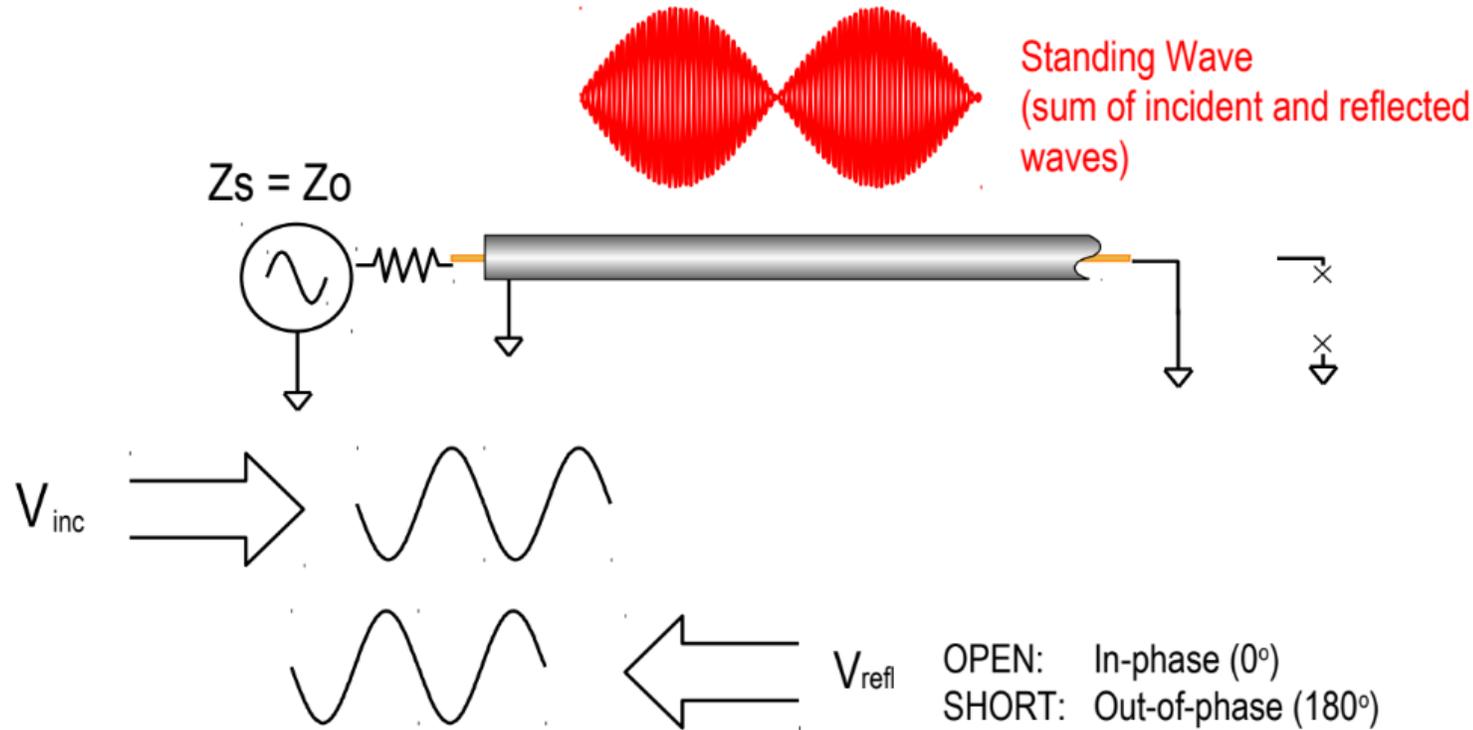
# SOL校准件



分析阻抗 $S_{11}$ : Smith chart

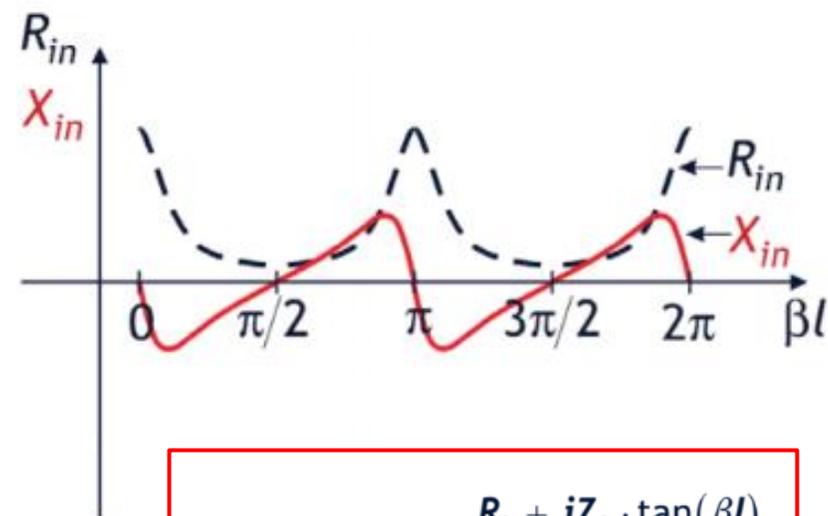
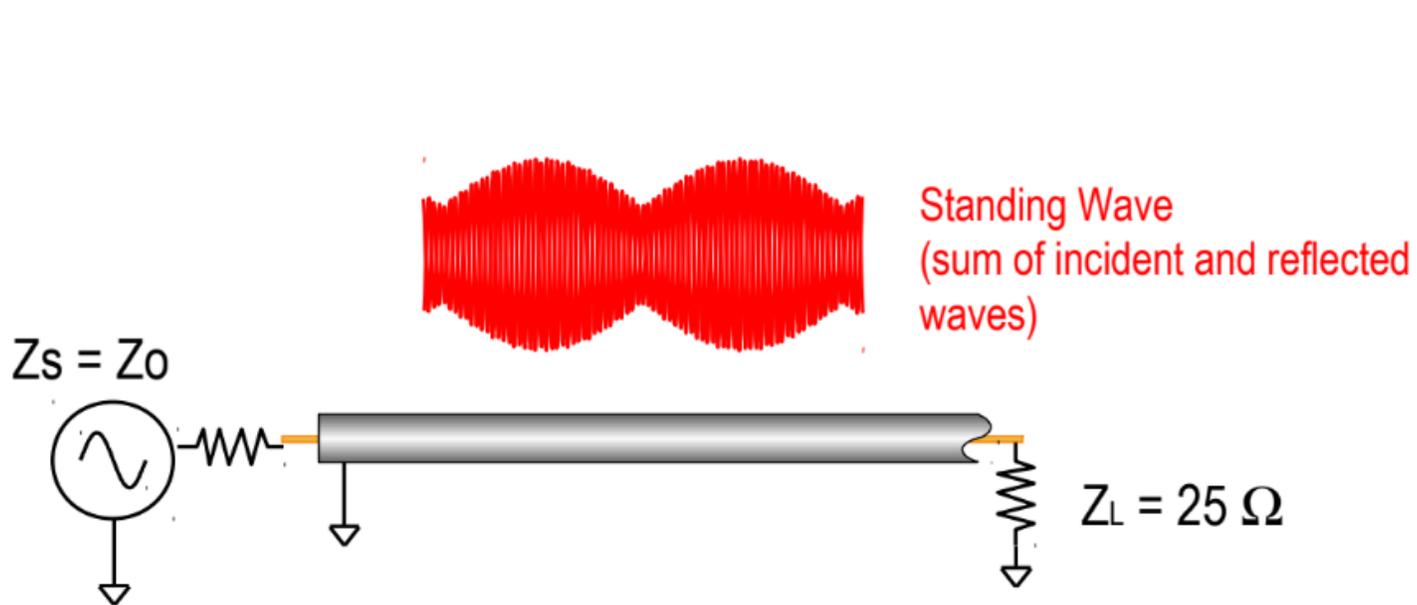


# 传输线+Short或者+Open

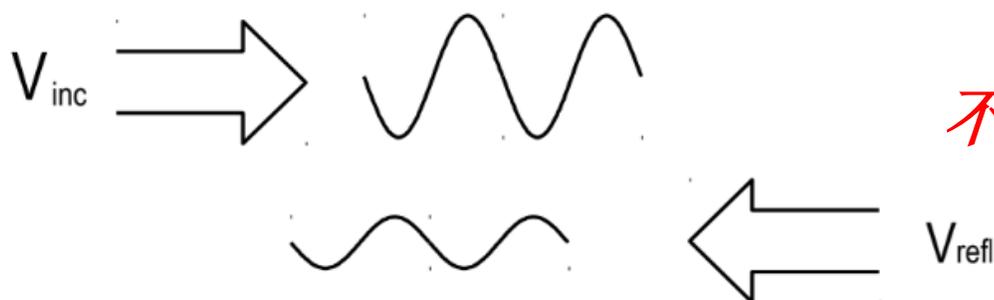


**Short和Open的情况，功率全返回到波源！**

# 传输线+Load (不匹配)

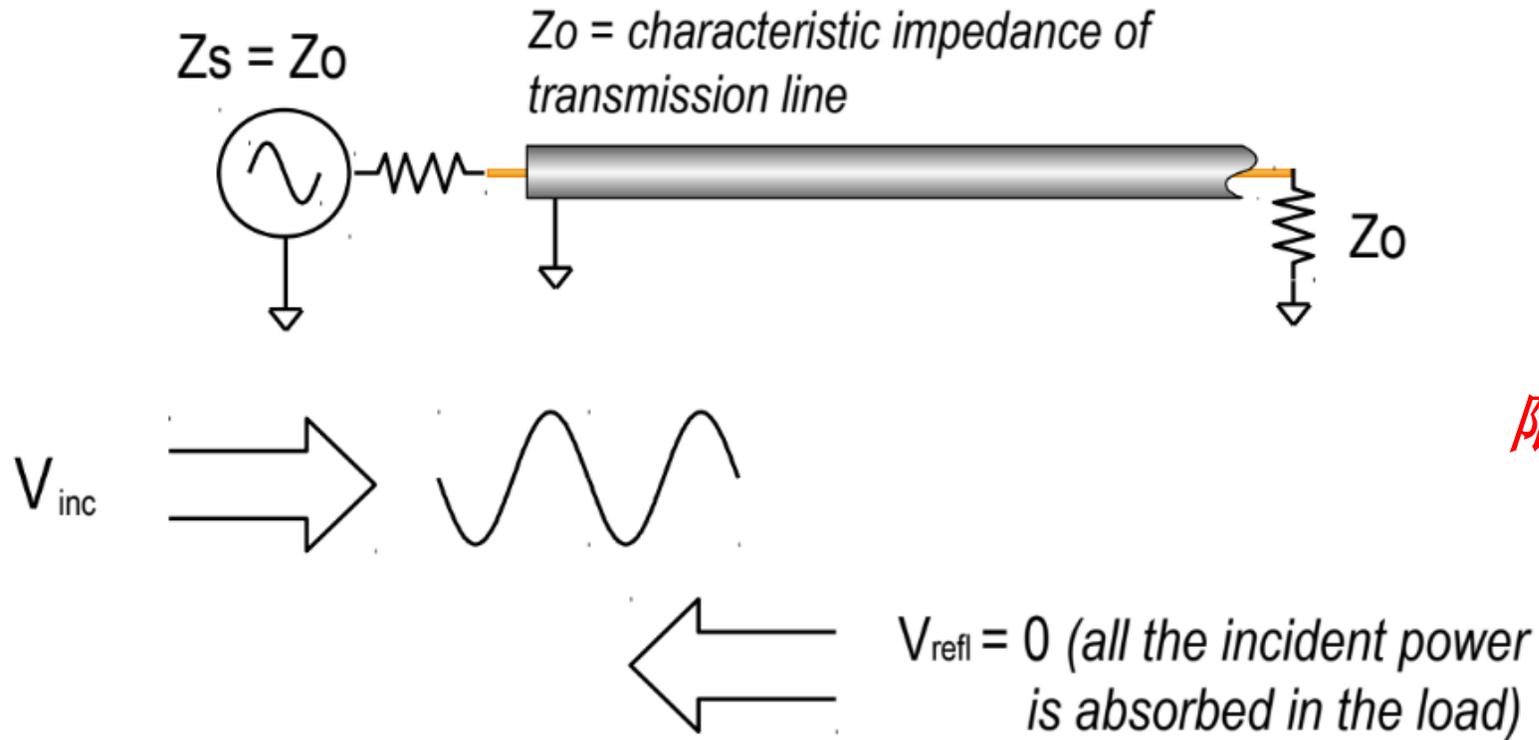


$$Z_{in} = Z(-l) = Z_0 \cdot \frac{R_L + jZ_0 \cdot \tan(\beta l)}{Z_0 + jR_L \cdot \tan(\beta l)}$$



驻波与Short和Open  
不同，不归0

# 传输线+Load



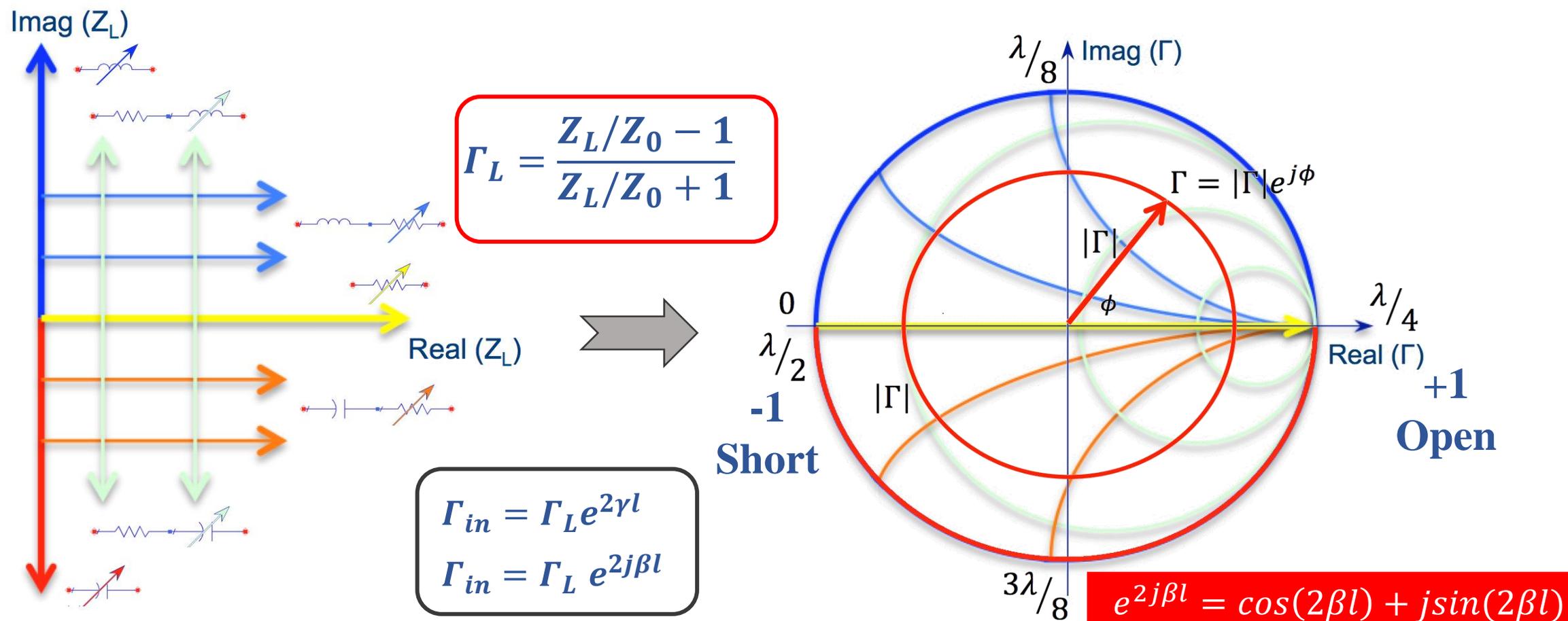
等效于一根无限长传输线!

# 阻抗与反射系数 $\Gamma_{in}$ 之间的关系

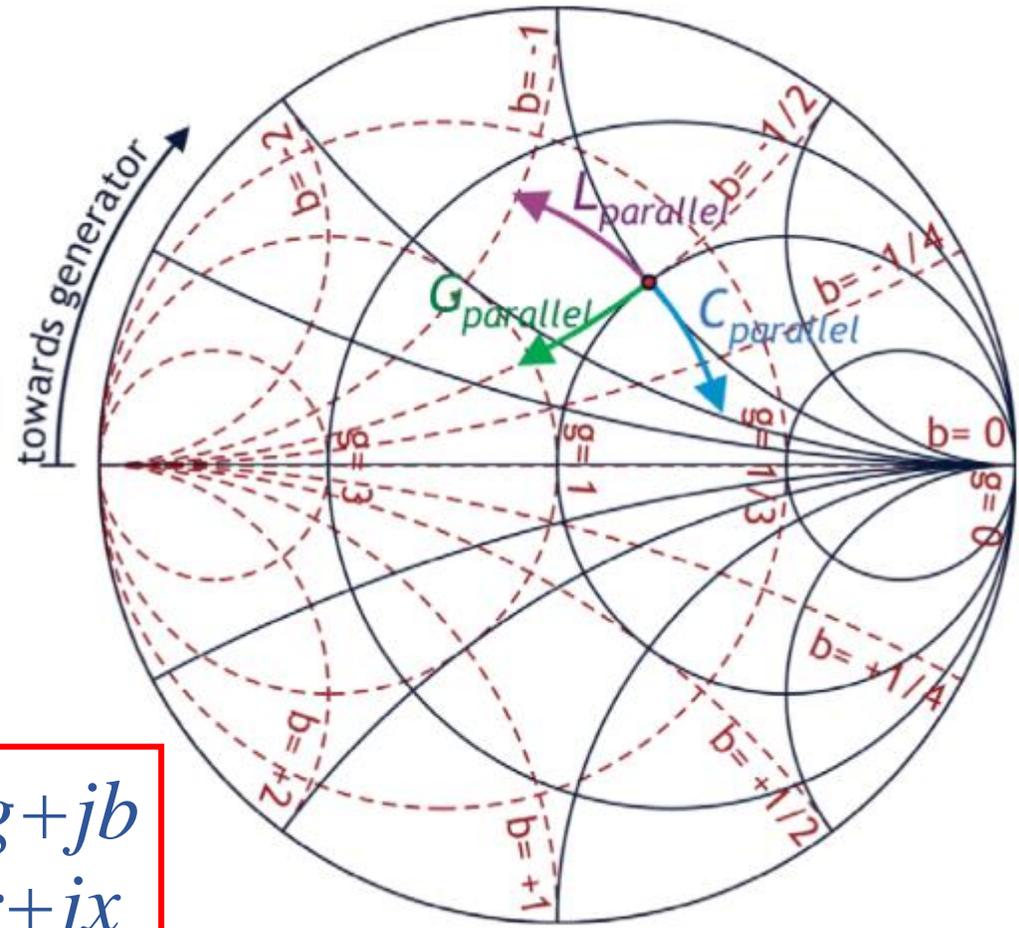
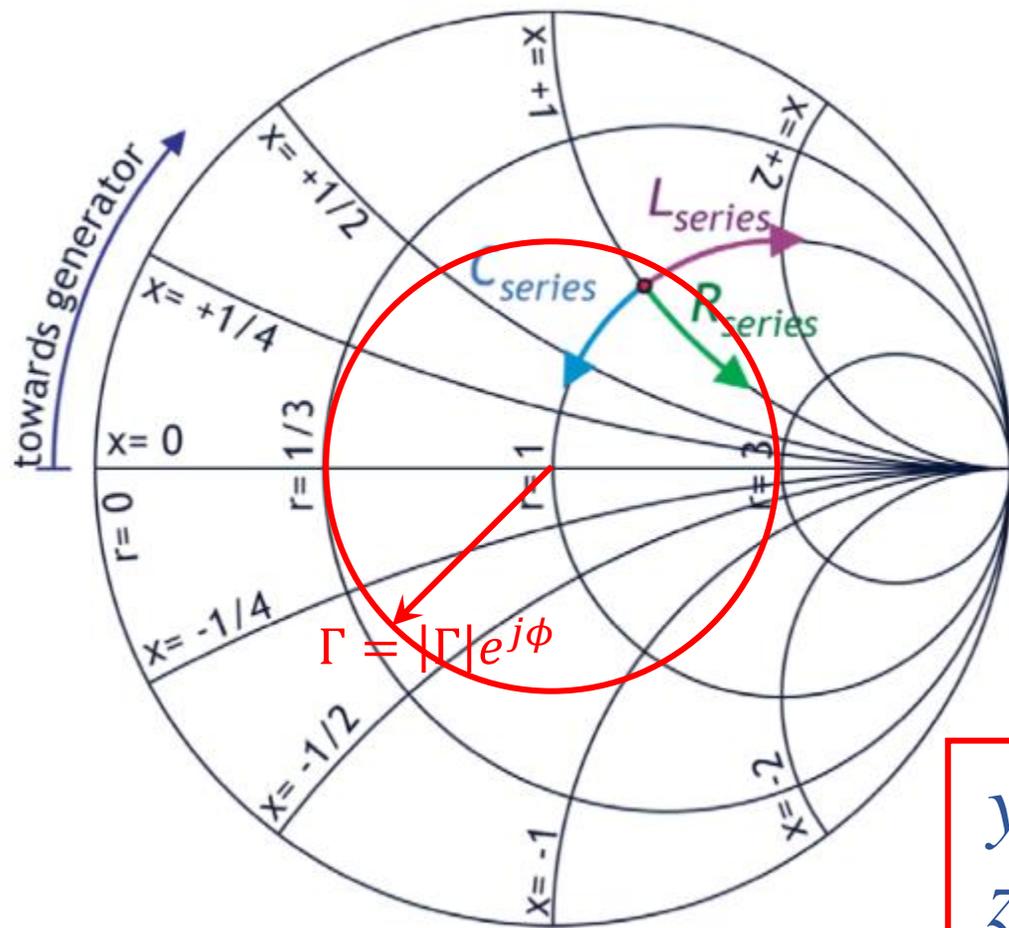
Line+general:	$Z_{in} = Z_0 \frac{Z_L + Z_0 \text{th}(\gamma l)}{Z_0 + Z_L \text{th}(\gamma l)}$ $Z_{in} = Z_0 \frac{Z_L + jZ_0 \text{tg}(\beta l)}{Z_0 + jZ_L \text{tg}(\beta l)} \quad (\text{无损耗})$	$\Gamma_{in} = \Gamma_L e^{-2\gamma l}$ $\Gamma_{in} = \Gamma_L e^{-2j\beta l}$	$\beta l = \frac{2\pi}{\lambda} l = \text{电长度}$	
Line+Short:	$Z_L = 0$	$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = -1$	$Z_{in} = Z_0 \text{th}(\gamma l) = jZ_0 \text{tg}(\beta l)$	$\Gamma_{in} = -e^{-2\gamma l} = -e^{-2j\beta l}$
Line+Open:	$Z_L = \infty$	$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = +1$	$Z_{in} = \frac{Z_0}{\text{th}(\gamma l)} = \frac{Z_0}{j \text{tg}(\beta l)}$	$\Gamma_{in} = e^{-2\gamma l} = e^{-2j\beta l}$
Line+Load:	$Z_L = Z_0$	$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = 0$	$Z_{in} = Z_0$	$\Gamma_{in} = 0$

# Smith图定义

由复数坐标系“Z-plane”转变为复数坐标系“Γ-plane”： $Z_L = R/Z_0 + jX/Z_0$



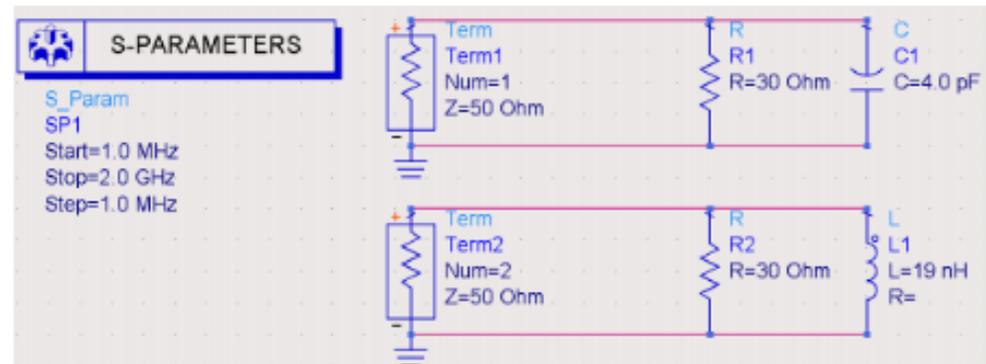
# Smith图的意义



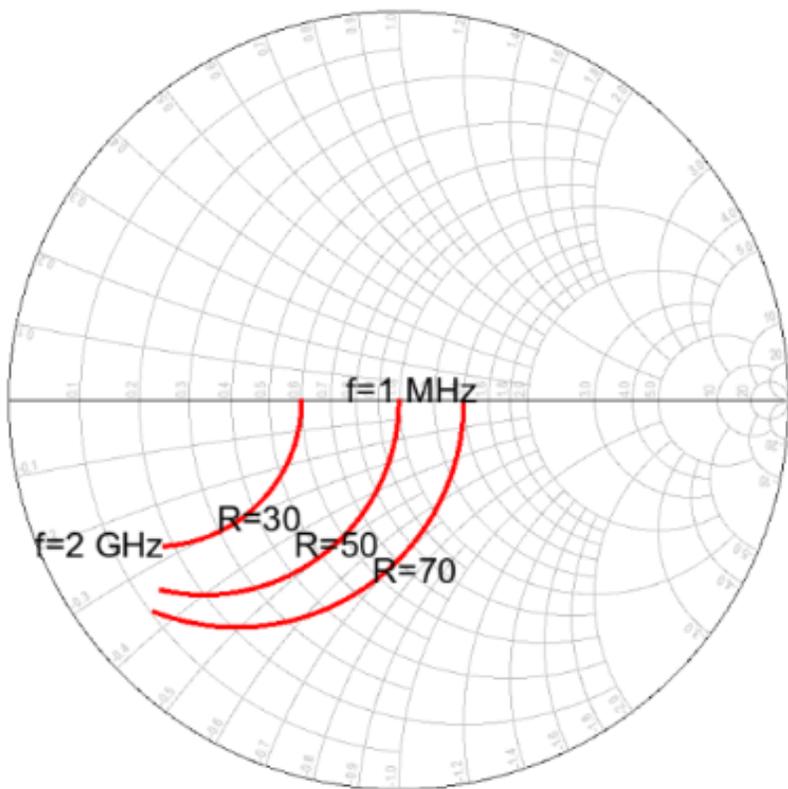
$$y = g + jb$$
$$z = r + jx$$

# Smith图解-并联

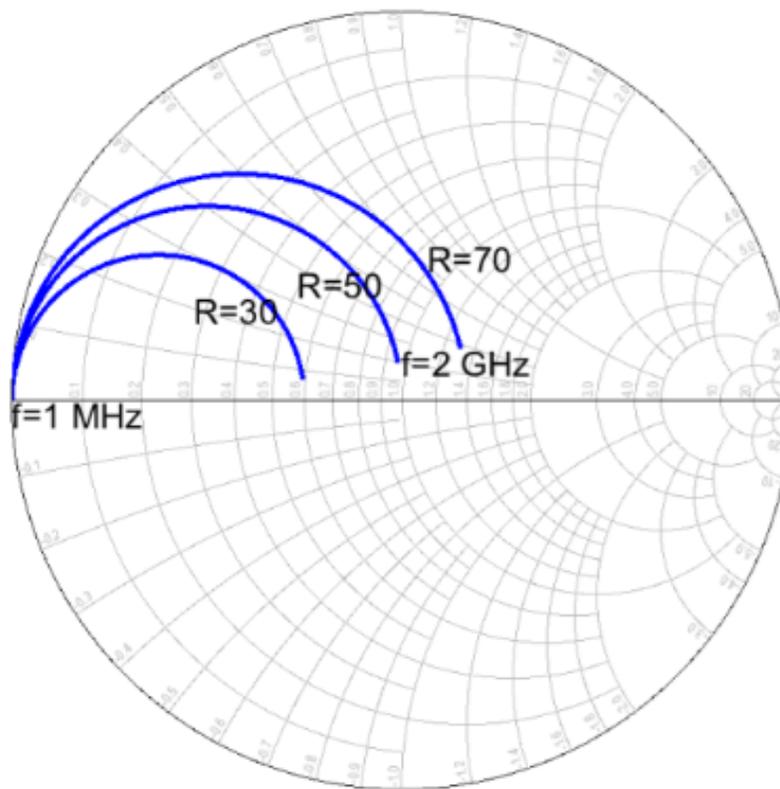
并联RC和RL电路 $\Gamma$ 的扫频变化



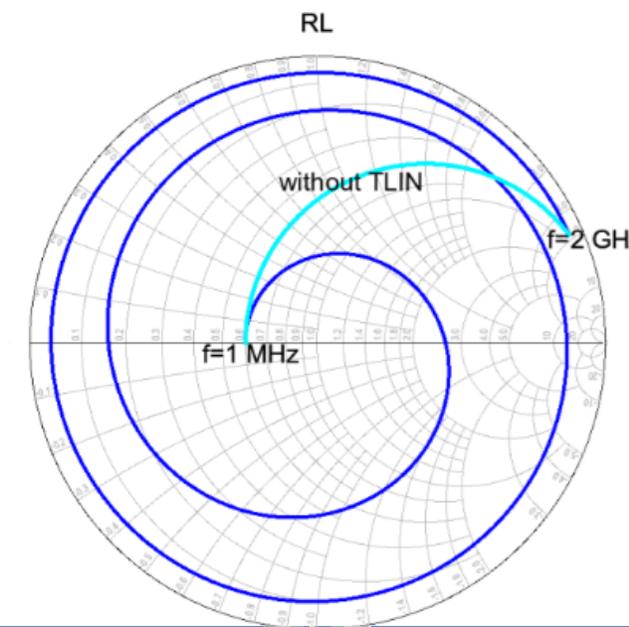
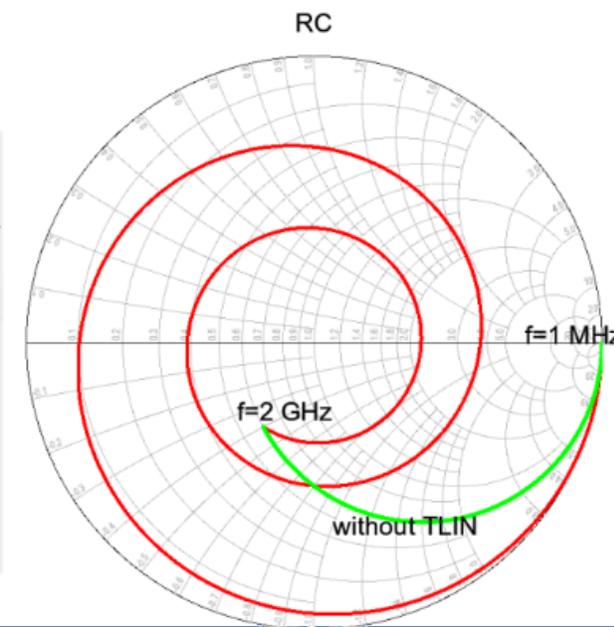
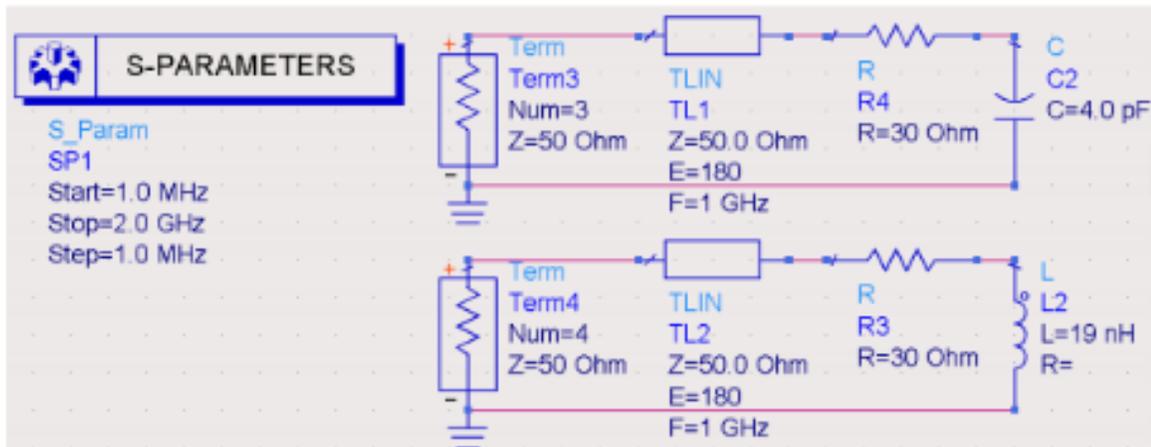
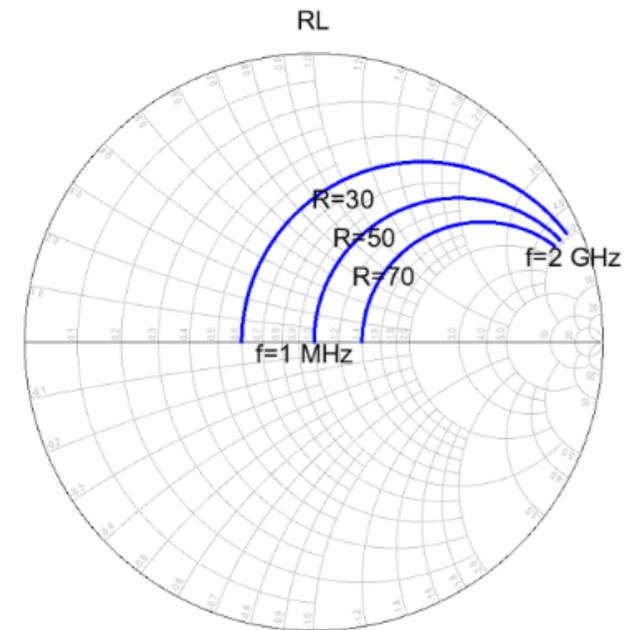
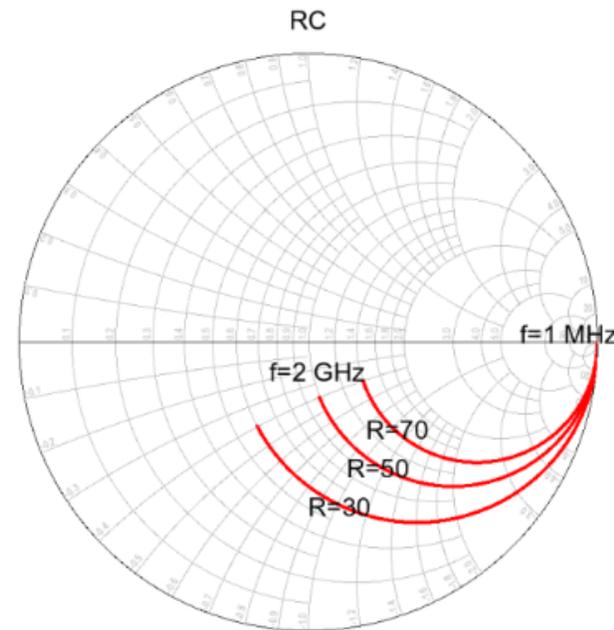
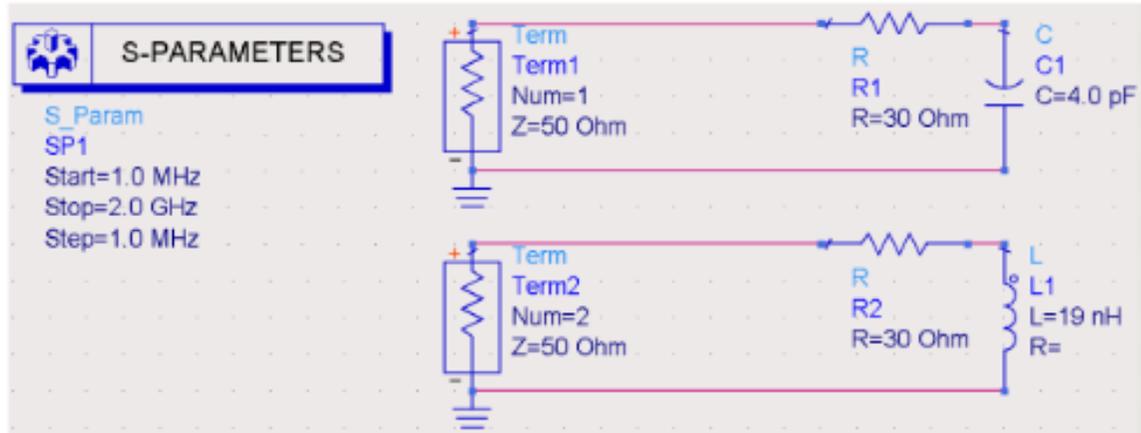
RC



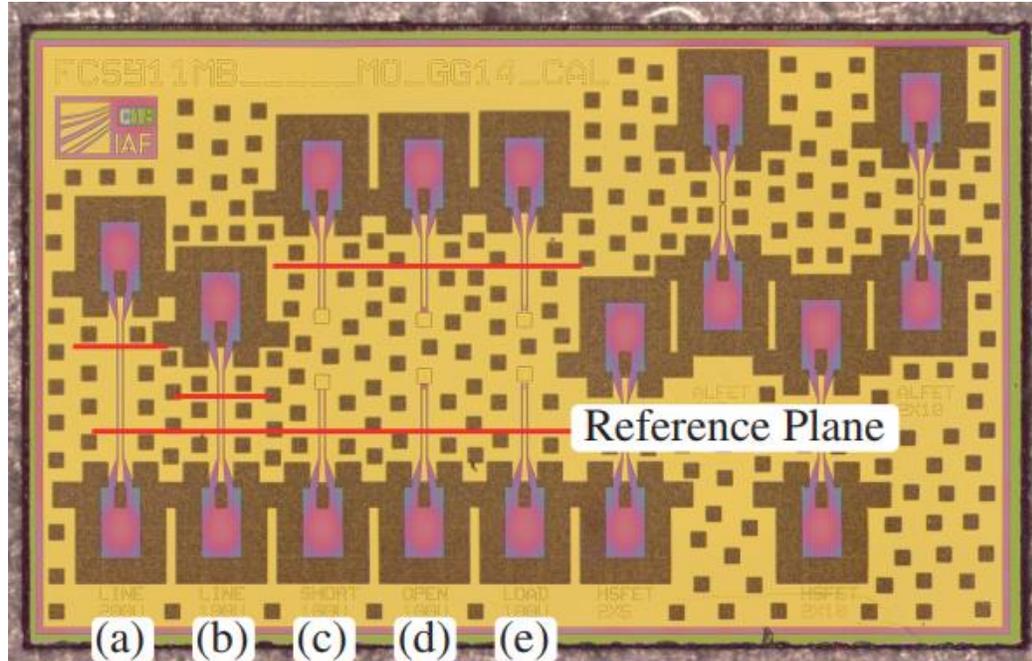
RL



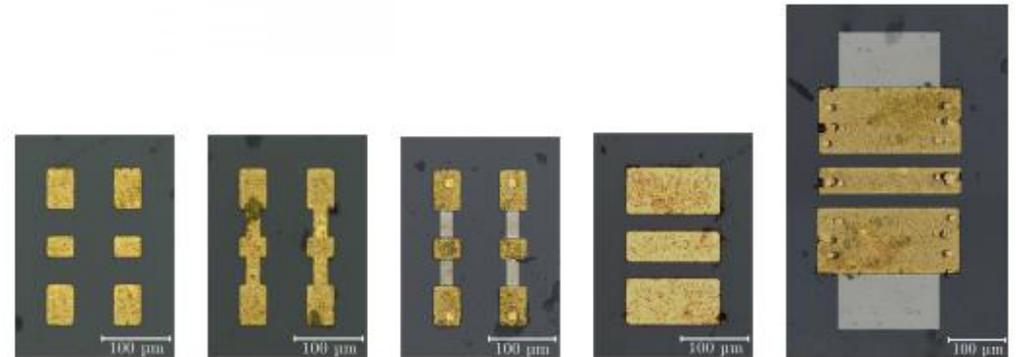
# Smith图解-串联



# 常见校准件



(a) line (b) thru (c) short (d) open (e) match



# 几种典型校准算法

- SOLT
- SOLR
- LRM
- TRL
- Series R

# SOLT(或TOSM)校准算法

S—short (reflect)

O—open in air (reflect)

L—load (parallel resistor)

T—thru

## **Short-open-load-thru:**

- 所有校准件需要准确定义(包括thru)
- Open有电容值(open in air经常为负电容)
- Short和Load都有电感值
- 对探针的放置很敏感(影响定义值)

# SOL校准（单端口校准）

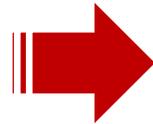
反射参数测量

$$S_{11A} = \frac{S_{11M} - E_D}{E_S(S_{11M} - E_D) + E_{RT}}$$

三个变量（复数变量），需要三个方程

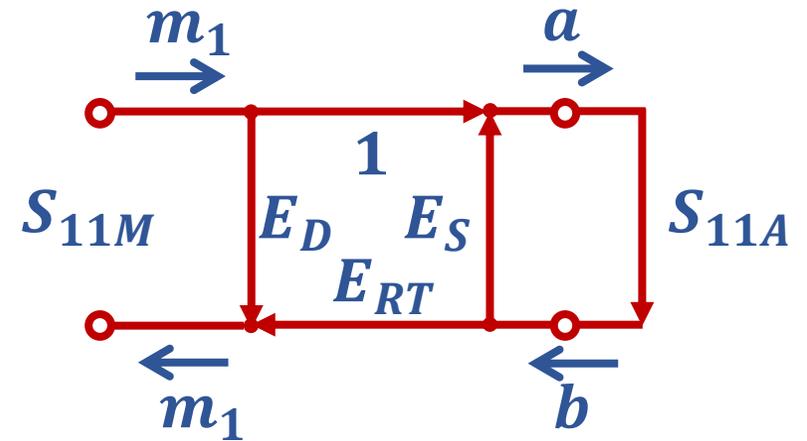
常用校准件：

- short
- open
- load



Port 1 的  $E_D$ ,  $E_S$ ,  $E_{RT}$

Port 2 的  $E'_D$ ,  $E'_S$ ,  $E'_{RT}$



# SOLT校准（双端口校准）

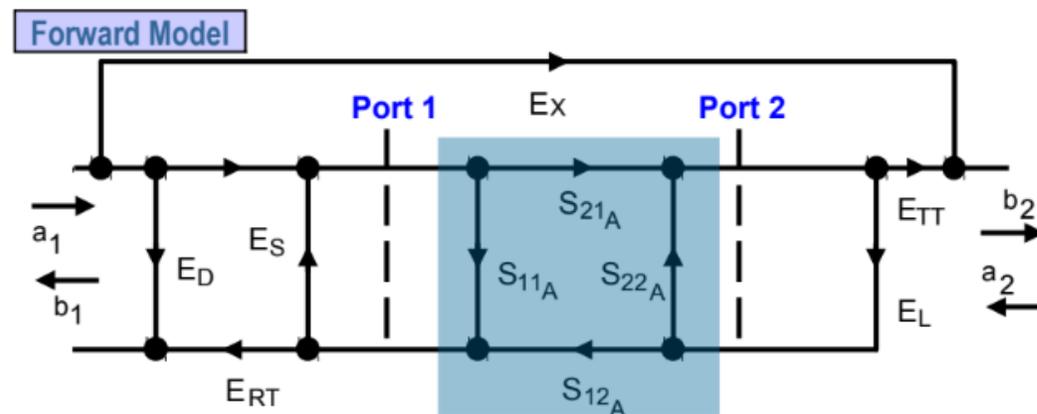
Step 1: 分别对双端口进行SOL校准;

Step 2: 引入thru

$$E_L = \frac{S_{11M} - E_D}{S_{11M}E_S - (E_DE_S - E_R)}$$

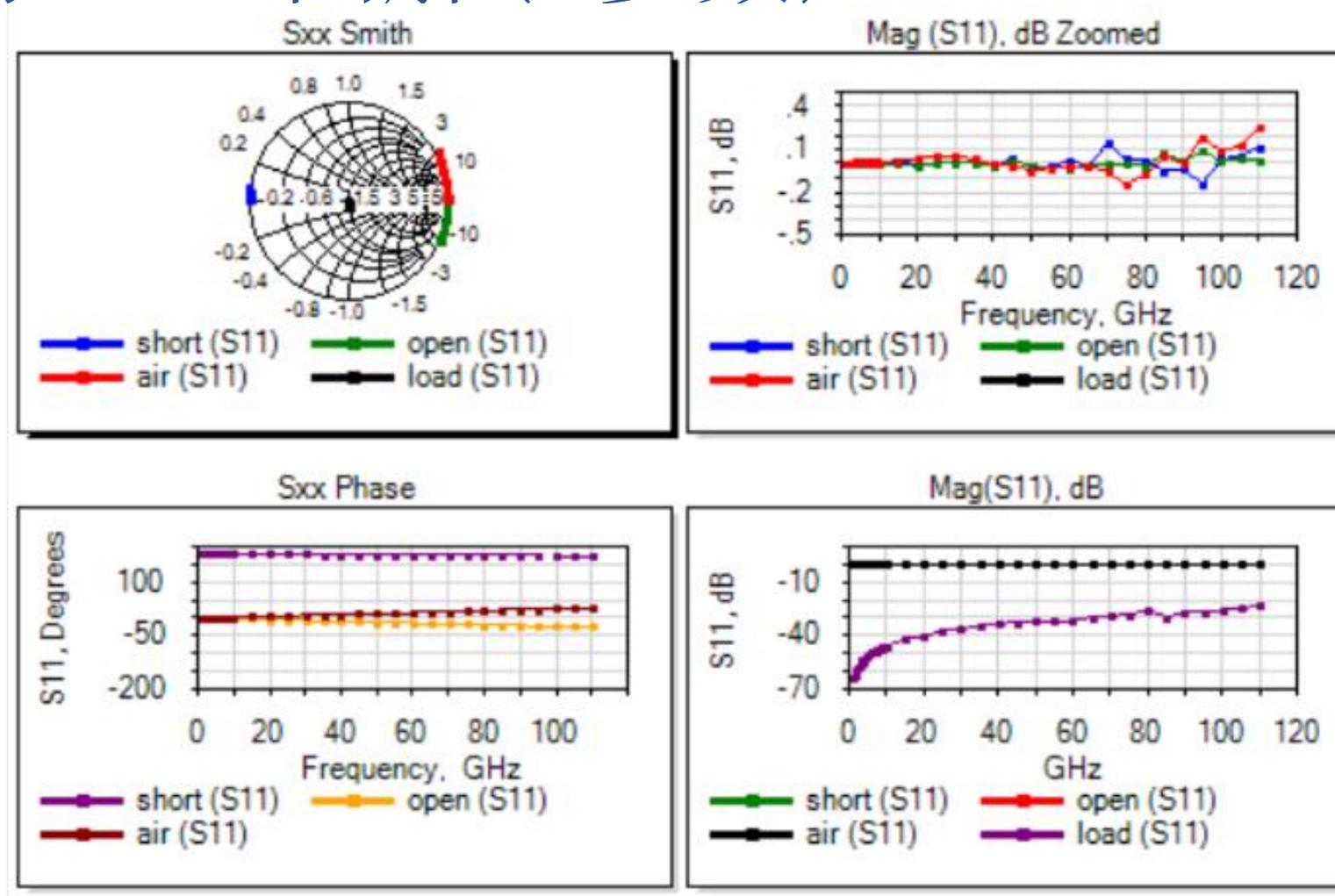
$$E_{TT} = S_{21M}(1 - E_SE_L)$$

对*reverse model*的5个参数同理



$$\begin{bmatrix} S_{11A} & S_{12A} \\ S_{21A} & S_{22A} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

# SOL的Smith图解 (S参数)



# SOLT校准件

一般由厂家提供定义文件。。。

校准件	要求	定义	举例
Thru/Line	Fully known	$S_{11}, S_{21}, S_{12}, S_{22}$ ; 或者 $R, L, C, G$ ; 或者 $\gamma, Z_c$ (4个已知量)	$Z_0=50\Omega$ $\alpha=0, \tau=0.5\text{pS}$
Open	$S_{11}$ (or $S_{22}$ ) known	2个已知量	$R=\text{inf}$ $C=0.3\text{fF}$
Short	$S_{11}$ (or $S_{22}$ ) known	2个已知量	$R=0$ $L=9\text{pH}$
Load(Match)	$S_{11}$ (or $S_{22}$ ) known	$Z=R+j\omega L$ , $R$ 和 $L$ 已知(2个已知量)	$R=50$ <b><math>L=10.6\text{pH}</math></b>

**SOLT的局限: 对所有件精确已知(实际值可能与定义值不符)**  
**一般用于40GHz一下频段校准.**

# SOLR校准算法

S—short (reflect)

O—open in air (reflect)

L—load (parallel resistor)

R—reciprocal thru (互易)

- 对Thru要求低，仅需满足 $S_{12}=S_{21}$
- 适用于DUT双端差 $90^\circ$ 度情况

非直线Thru:



# SOLR校准算法

适用于波导等，尤其端口相对位置特殊的情况

校准件	要求	定义	举例
Reciprocal	unknown, $S_{21}=S_{12}$	1个已知量	$S_{21}=S_{12}$
Open	$S_{11}$ (or $S_{22}$ ) known	2个已知量	$R=\text{inf}$ $C=0.3\text{fF}$
Short	$S_{11}$ (or $S_{22}$ ) known	2个已知量	$R=0$ $L=9\text{pH}$
Load(Match)	$S_{11}$ (or $S_{22}$ ) known	2个已知量 $Z=R+j\omega L$ , $R$ 和 $L$ 已知	$R=50$ $L=10.6\text{pH}$

# LRM和LRM+校准算法

L—line (thru)

R—reflect (short或者open in air)

M—match (parallel resistor)

- Match是无限长高损耗传输线(类比TRL里的line);
- 单个Line可以保证固定探针间距
- Reflect无需定义， Match和Line需要准确定义;
- 可采用ISS校准片实现， 但Match会影响较大;
- 仅需测量单个load校准件

# LRM和LRM+校准算法

LRM主要用于同轴测量（参考阻抗50Ω）

LRM+主要用于在片测量

当用short校准时, open可用来验证

校准件	要求	定义
Thru/Line	Fully known	R, L, C, G; 或者 $\gamma$ , $Z_c$ (4个已知量)
Reflect (Open/Short)	unknown, $S_{11}=S_{22}$	1个已知量
Load(Match)	$S_{11}$ and $S_{22}$ , known	<b>LRM:</b> $Z=R+jX$ , $R_1=R_2=50\Omega$ , $X_1=X_2=0$ , <b>LRM+:</b> $R_1, R_2$ 任意, $X_1, X_2$ 任意

**LRM的局限:** Load双端口的阻抗可能是不对称的。 (LRM需要Load对称, 难以满足)

# LRRM校准算法

L—line (thru)

R—reflect (short)

R—reflect (open in air)

M—match (parallel resistor)

- Match是无限长高损耗传输线(类比TRL里的line);
- 单个Line可以保证固定探针间距
- Match和Line必须准确定义;
- 可采用ISS校准片实现;
- 仅需测量单个load校准件

# LRRM校准算法

LRRM主要用于宽频带ISS off-wafer校准

校准件	要求	定义
Thru/Line	Fully known	R, L, C, G; 或者 $\gamma$ , $Z_c$ (4个已知量)
Reflect (Open)	unknown, $S_{11}=S_{22}$	1个已知量
Reflect(Short)	unknown, $S_{11}=S_{22}$	1个已知量
Load(Match)	$S_{11}$ (or $S_{22}$ ) known	$Z=R+j\omega L$ , R已知(1个已知量), L已/未知 (如eLRRM, cLRRM等自动求L)

*Load可能存在并联电容，尤其在高频时需要考虑。。。*

# TRL和MultilineTRL校准算法

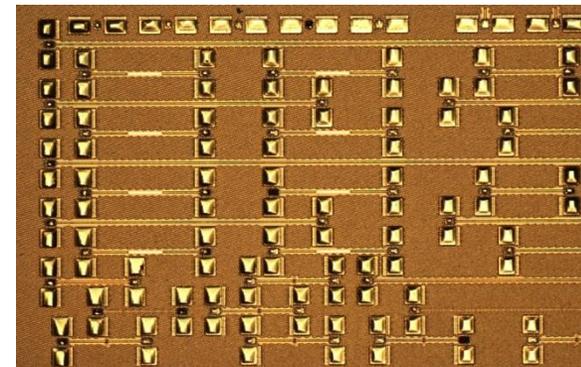
适合于非同轴环境测量，例如 PCB 上表贴器件，波导，夹具，片上测量

**Thru-Reflect-Line** (可与LRM对比分析):

- 无需定义校准件
- S参数以Line的特性阻抗为参考(其他多以load阻抗)
- 参考平面在thru中间(可通过算法移到端口)
- 探针间距不固定
- Line的阻抗是随frequency变化的(低频比较复杂)

# TRL和MultilineTRL校准算法

- 定义要求低
- 参考端面一般在Thru的中心



校准件		定义	作用
Thru		$S_{21}=S_{12}=1$ $S_{11}=S_{22}=0$	决定大部分校准参量
Reflect		$S_{11}=S_{22}$	决定参考端面的位置
Line		$S_{11}=S_{22}=0$ $S_{21}=S_{12}$	决定参考阻抗 $Z_0$ 测量 $\gamma$ 的值

# 如何使Line和Thru不同？

无损耗传输线阻抗有 $\lambda/4$ 变化性和 $\lambda/2$ 重复性

$\frac{1}{4}$  波长传输线的特点：90度相移，可以将开路/短路变短路/开路

$$Z_{in} = Z_0 \frac{Z_L + Z_0 \text{th}(\gamma l)}{Z_0 + Z_L \text{th}(\gamma l)}$$

$$\Gamma_{in} = \Gamma_L e^{-2\gamma l}$$

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \text{tg}(\beta l)}{Z_0 + jZ_L \text{tg}(\beta l)} \text{ (无损耗)}$$

$$\Gamma_{in} = \Gamma_L e^{-2j\beta l}$$

$$\beta l = \frac{2\pi}{\lambda} l = \text{电长度}$$



转半圈



90度



$\lambda/4$

# 传输线相位变化

$$e^{2j\beta l} = \cos(2\beta l) + j\sin(2\beta l)$$

$$\Gamma_L = \frac{Z_L/Z_0 - 1}{Z_L/Z_0 + 1}$$

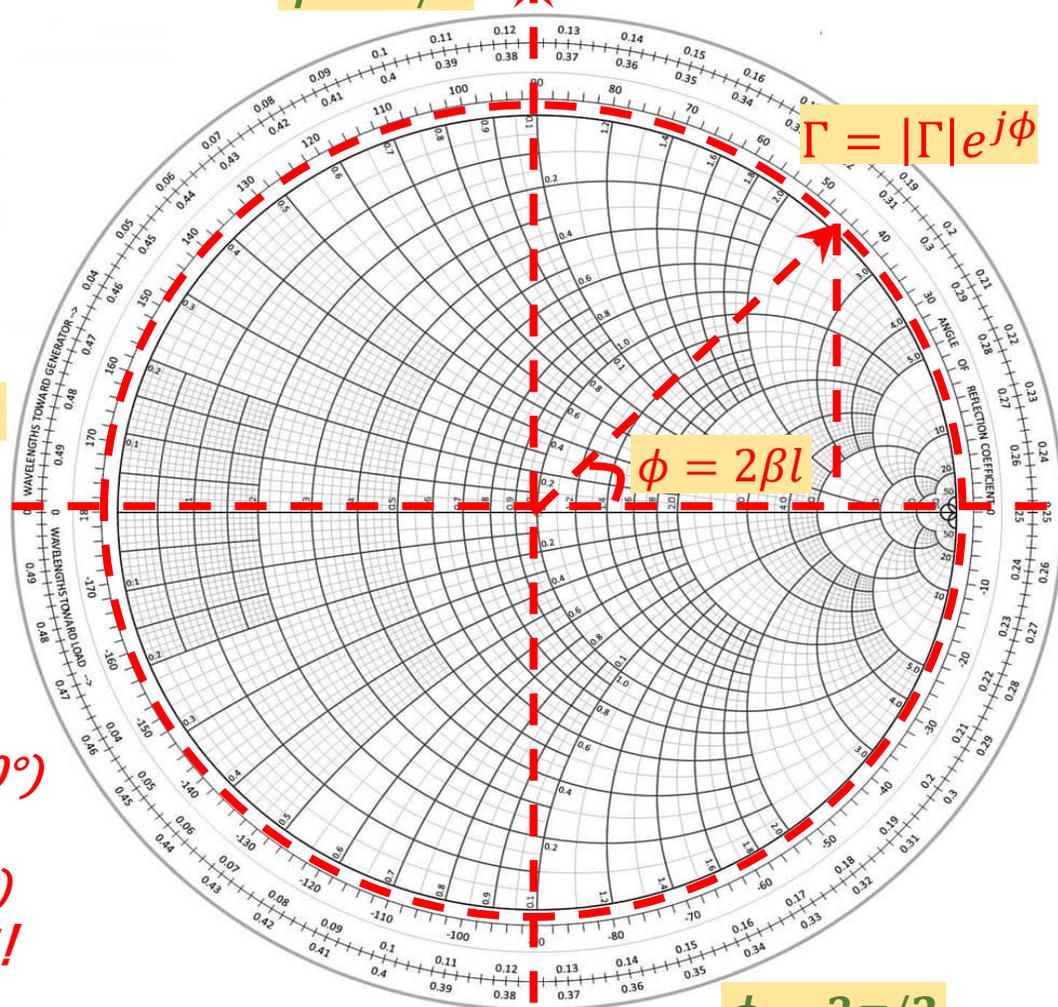
电长度:  $E = \beta l = \frac{2\pi}{\lambda} l$

$$\phi = 2\pi$$

$$l = \frac{\lambda}{2}$$

$$l = \frac{\lambda}{8}$$

$$\phi = \pi/2$$



$$\phi = 2\beta l = \frac{4\pi}{\lambda} l$$

$$l = \frac{\phi}{4\pi} \lambda$$

$$l = \frac{\lambda}{4}$$

$$\phi = \pi$$

两条输线相差  $\lambda/4$  ( $E=90^\circ$ ) 时相位差最大!

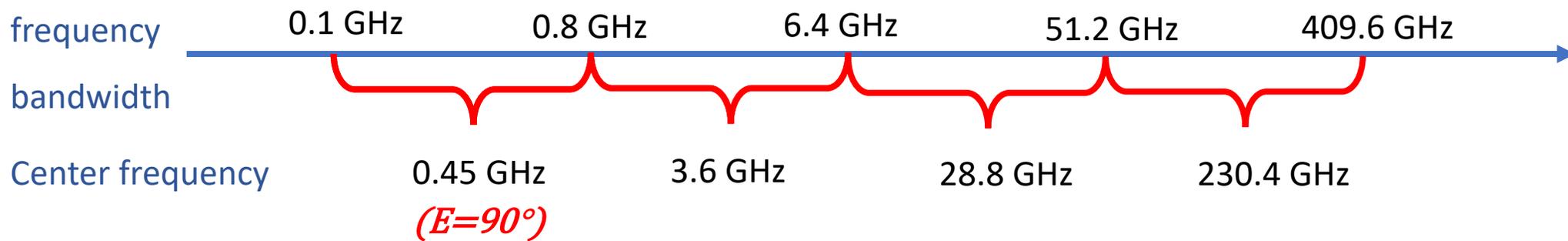
相位差在  $< \lambda/18$  ( $E=20^\circ$ ) 和  $> 4\lambda/9$  ( $E=160^\circ$ ) 很难分辨!

$$\phi = 2\beta l = \frac{3\lambda}{8}$$

$$\phi = 3\pi/2$$

# Line长度设置

频带的频率差不能超过8倍!



Step 1: 确定带宽和Line的数量    对于给定频率如何均分带宽?

Step 2: 计算中心频率和其波长    如何计算波长?

Step 3: 确定Line的长度    中心频率的1/4波长, easy!

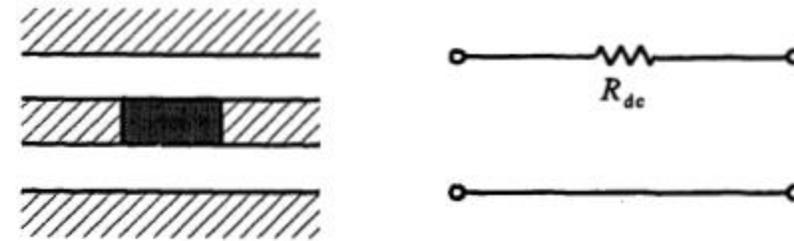
# Series-Resistor校准算法

L—Thru

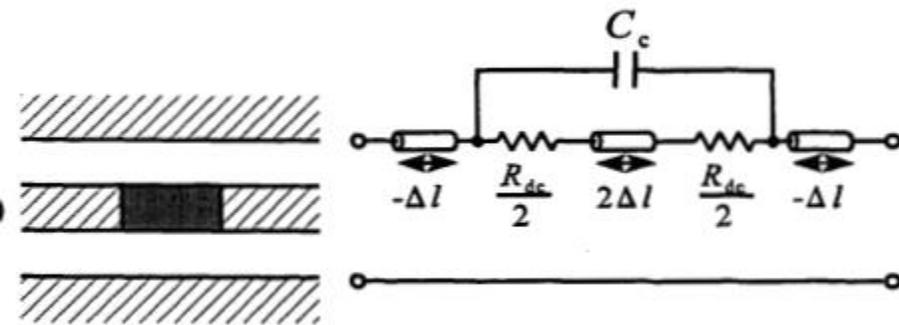
R—reflect (一般为open)

S—Series resistor

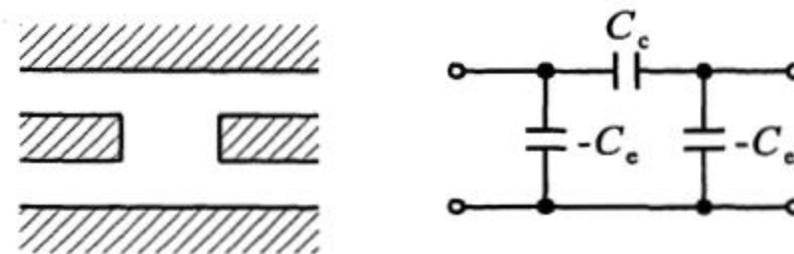
- 参考端面在电路的中心
- 类似LRM (M是parallel resistor)
- Reflect需要对称 $S_{21}=S_{12}$
- 需要对Series resistor精确建模



简化电路



分布电路



用于计算  
 $C_c$ 和 $C_e$

# Series-Resistor校准算法

LRM: 需要Load对称, 固定间距

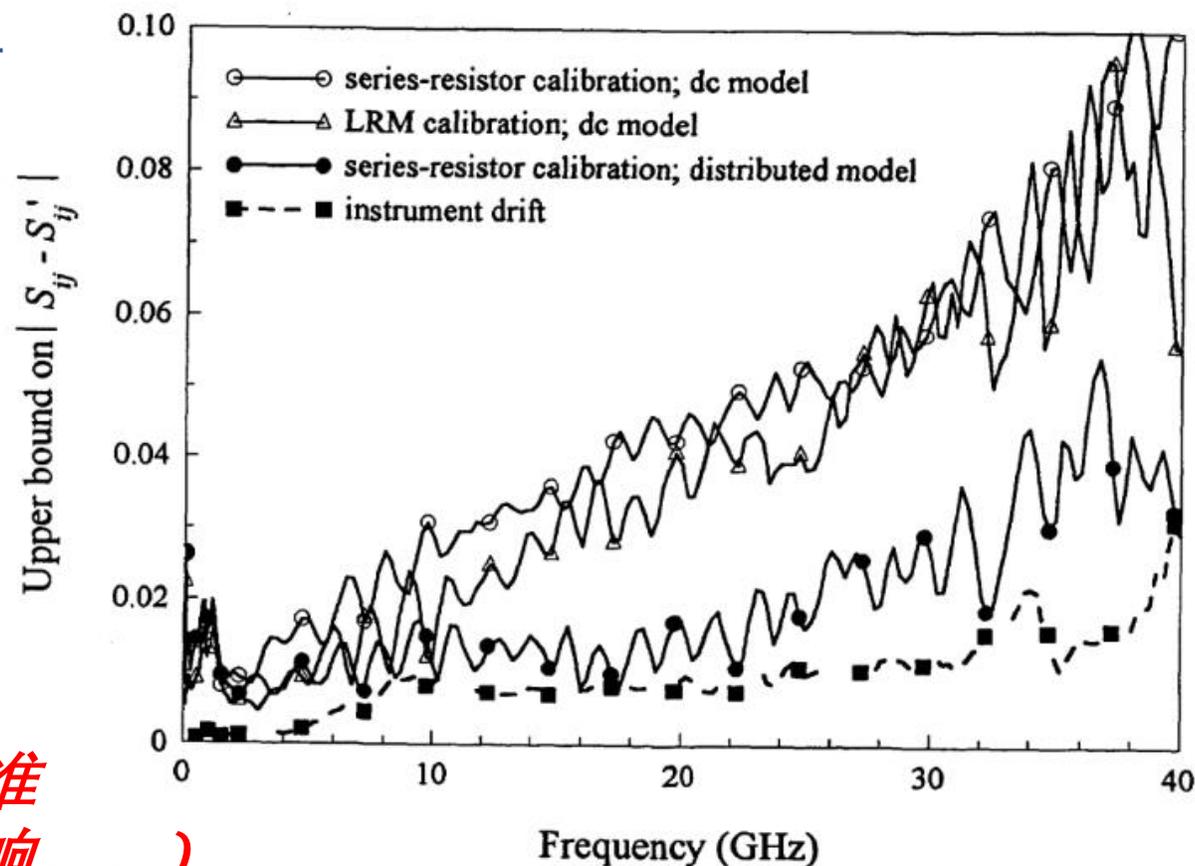
TRL: Line太长, 精度高

LRS: 固定间距+高精度

精确获得串联电阻电路:

- 额外设计一个series open
- 测量series resistor的DC电阻

**对于校准件的精确建模和表征, 是校准的重要环节! (考虑频率的影响。)**

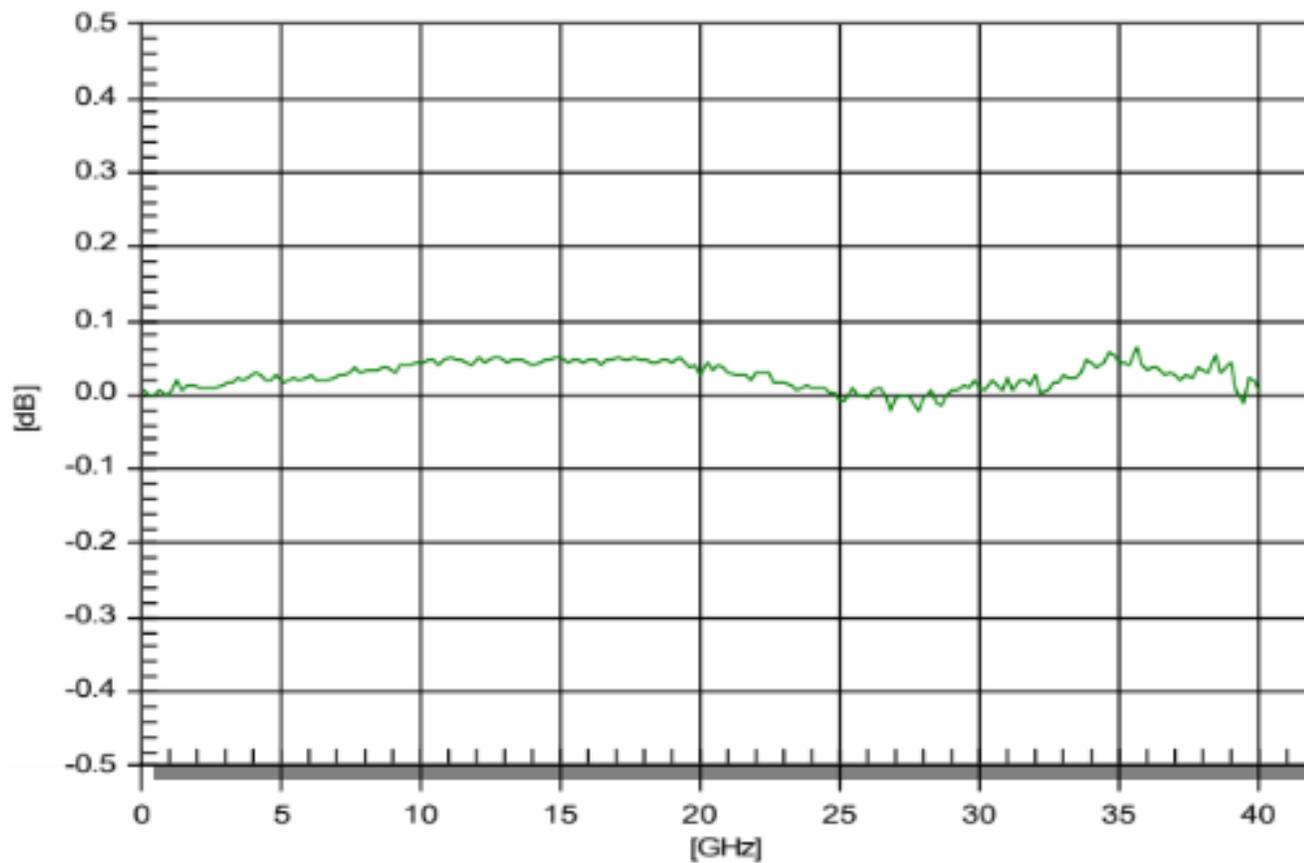
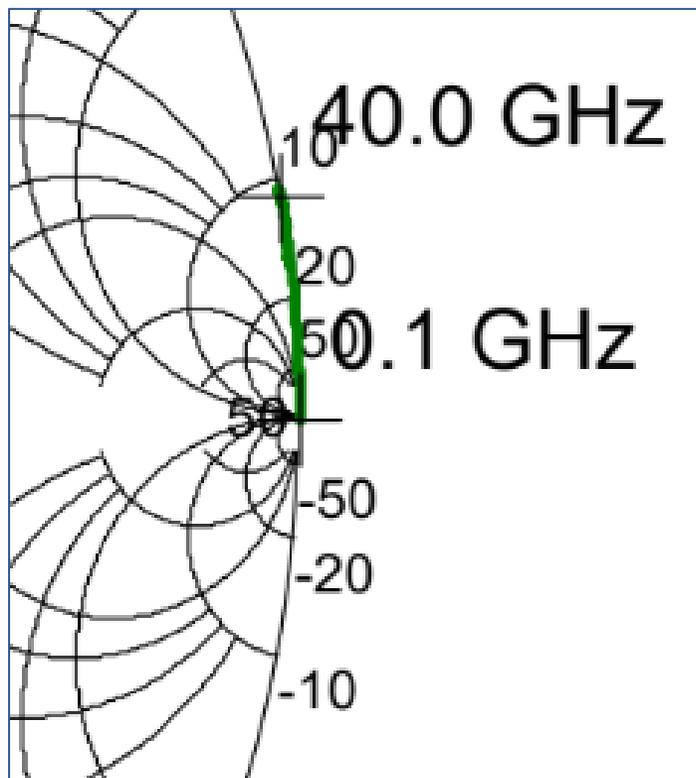


# 校准完成后如何校验？



# 如何验证校准

空悬探针(Open in air)

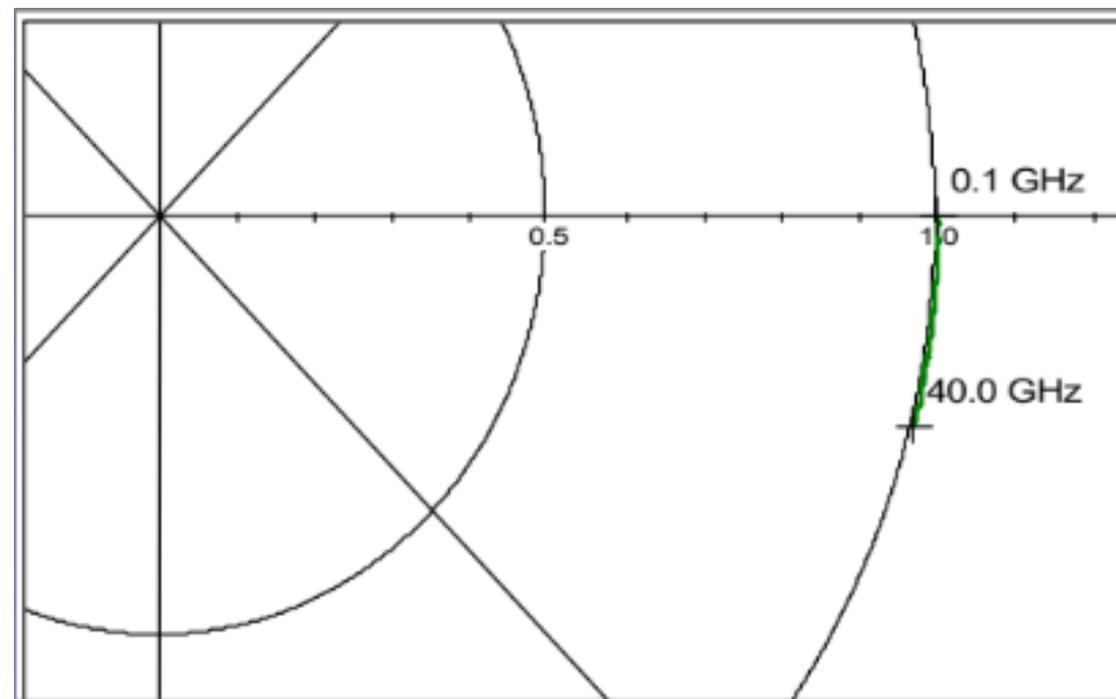
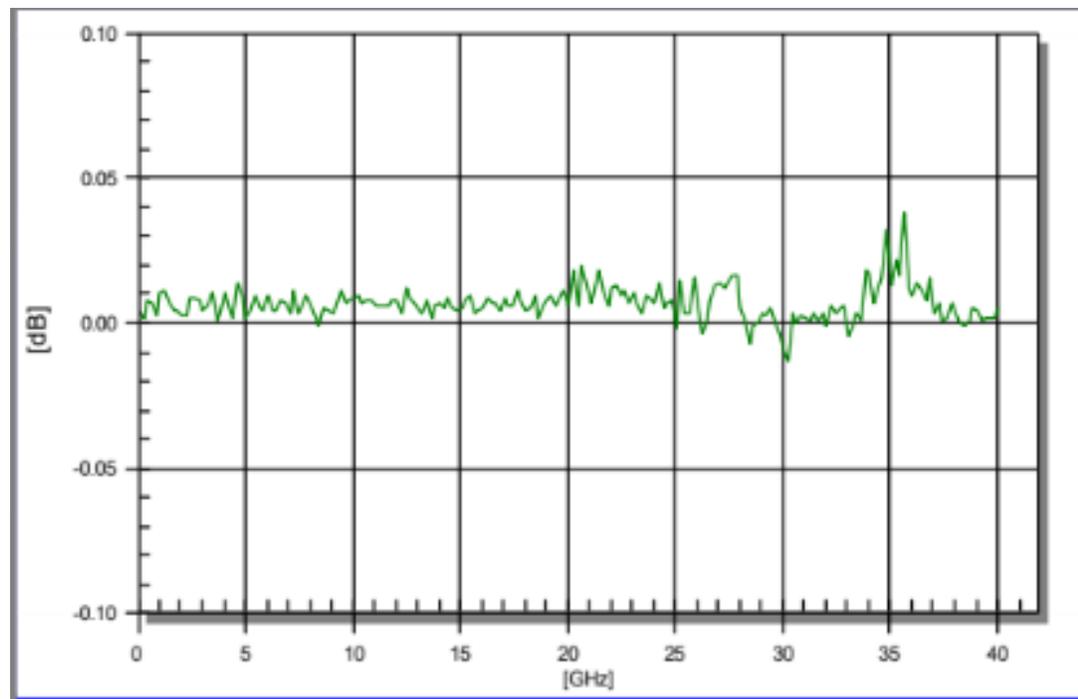


单位增益+负电容。。。

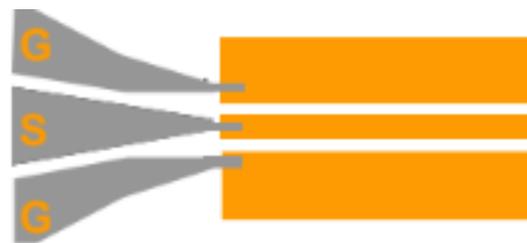
# 如何验证校准

测量Thru线

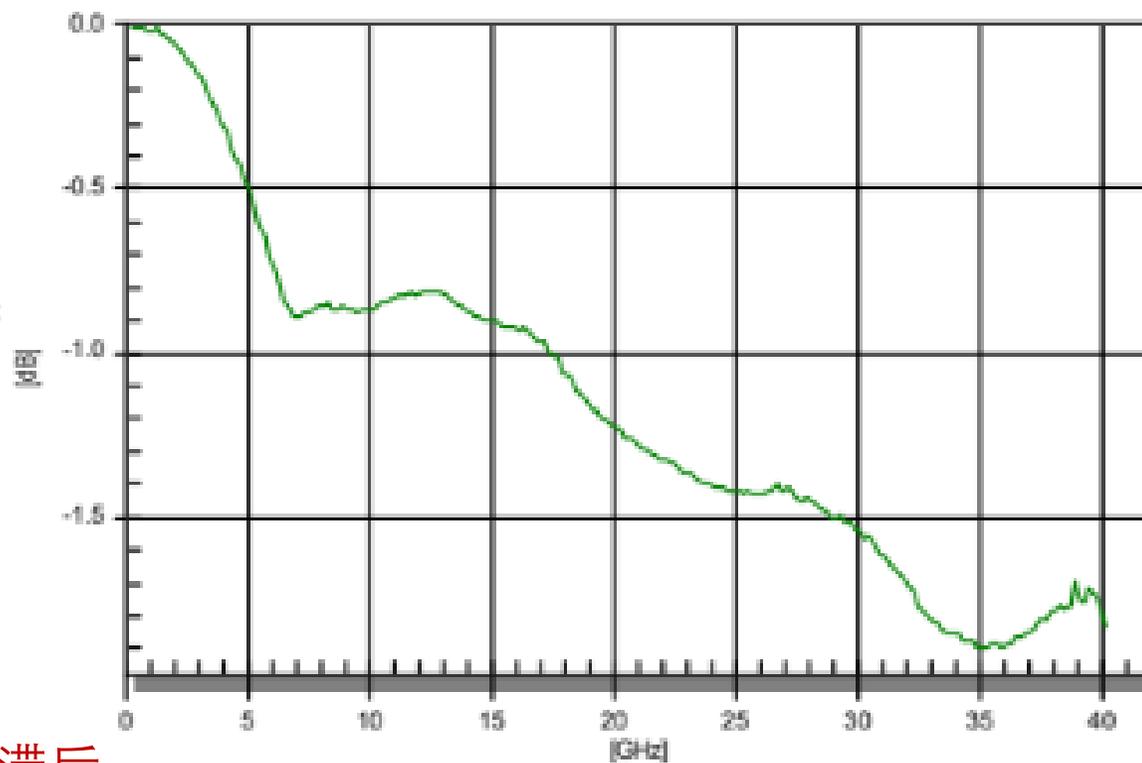
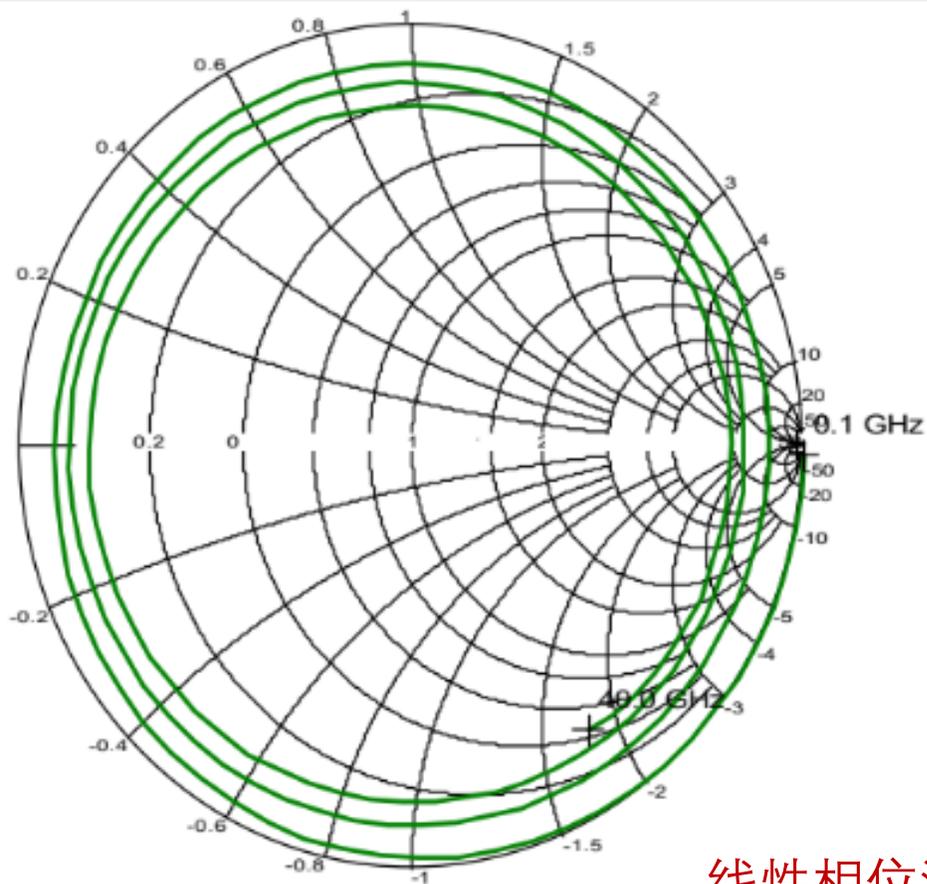
一般不建议再次测量校准件！



# 如何验证校准



测开路短截线



线性相位滞后。。。

# 校准算法对比分析

了解校准算法的基本机理和局限很关键!

校准方法	应用场合	提高测量精度: VNA硬件性能 误差的模型 校准算法 校准件
SOLT	4个校准件需精确定义; 用于小于40GHz范围	
SOLR	R-reciprocal (Thru未知) 探针角度位置不强求在一条线上	
LRM	不建议用于在片测量	
LRM+	可用于在片, 固定探针间距, 需Load对称	
LRRM	可用于在片, 固定探针间距, 仅需Load的S11	
(Multiline)TRL	精确在片校准, 但探针间距不固定	
Series-resistor	精确, 探针间距固定, 但电阻不容易制作和表征	