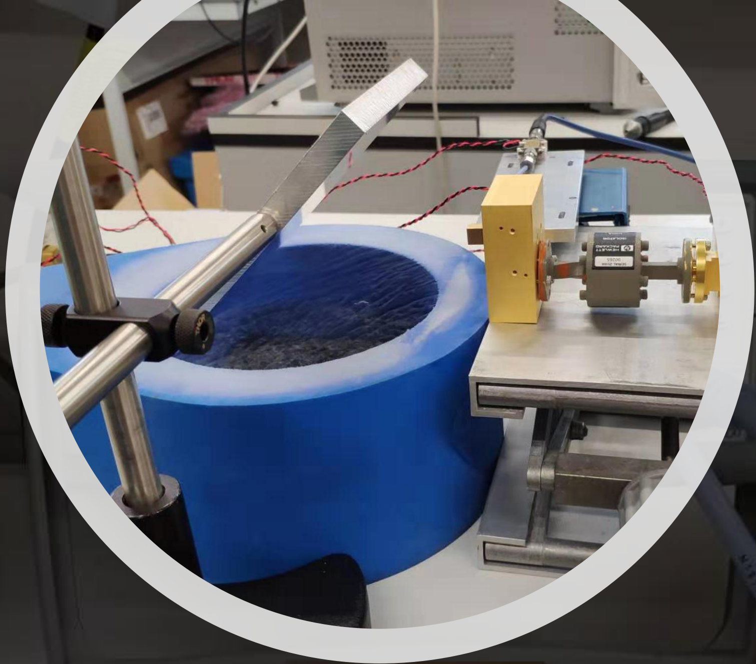
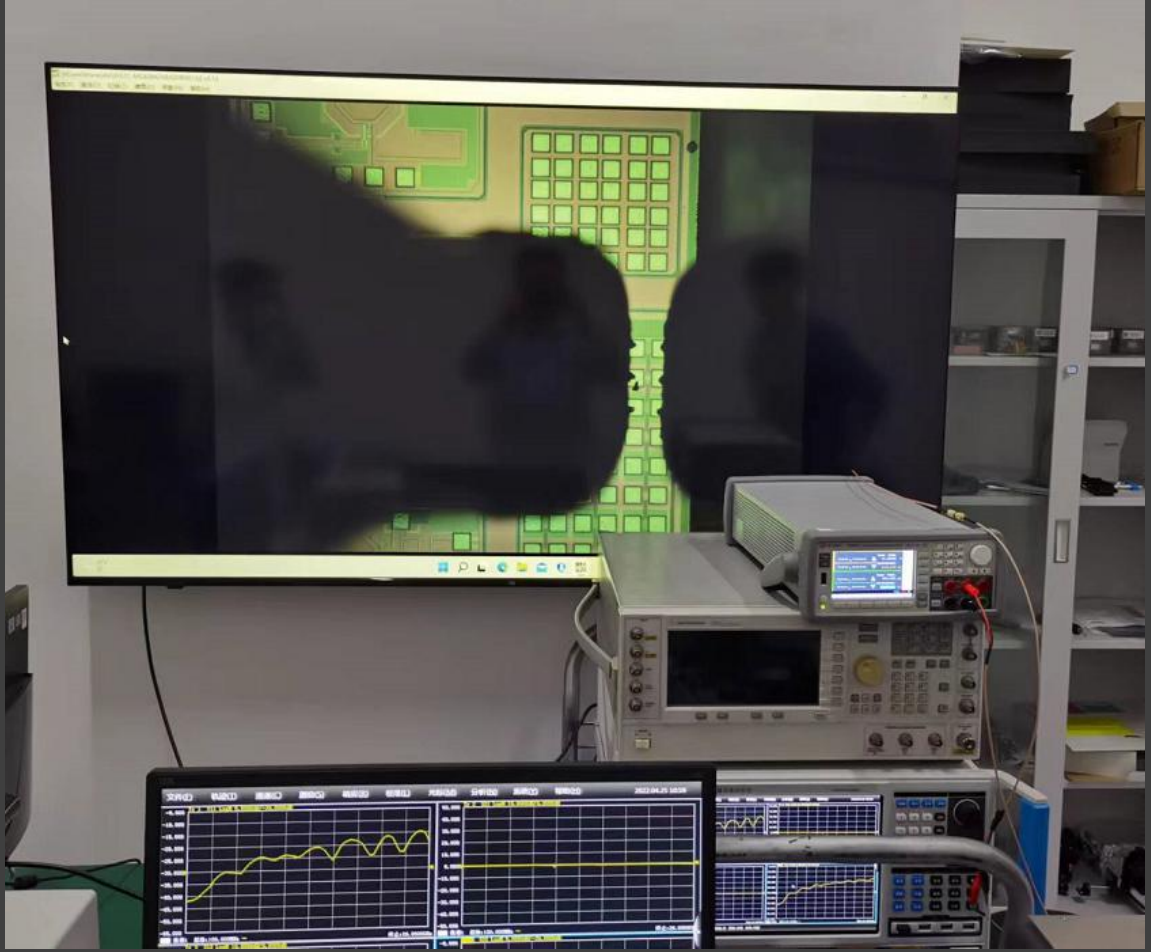
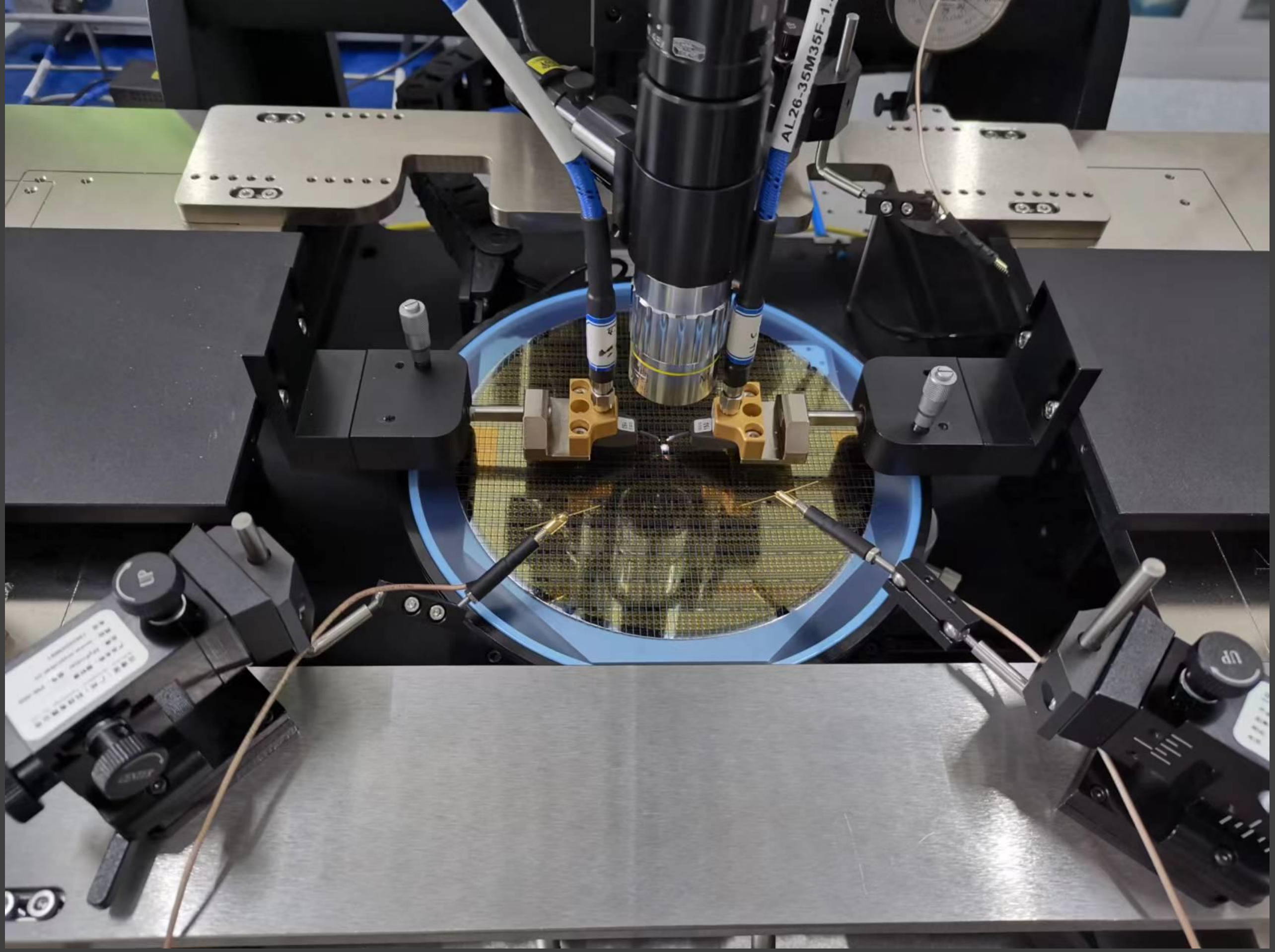


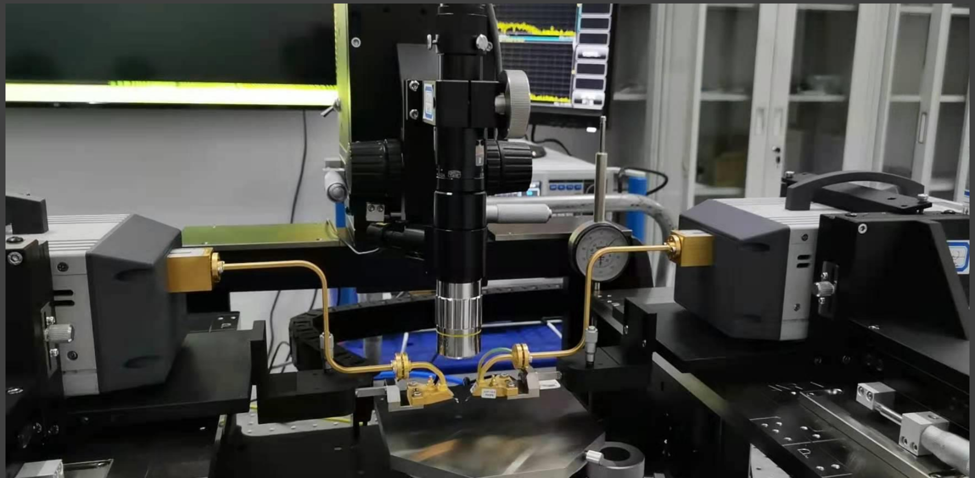
电子科技大学暑期课程
微波测量基础

授课教师：郭诚

西安交通大学 电子与信息工程学院







第三讲：校准与在片测试

授课教师：郭诚

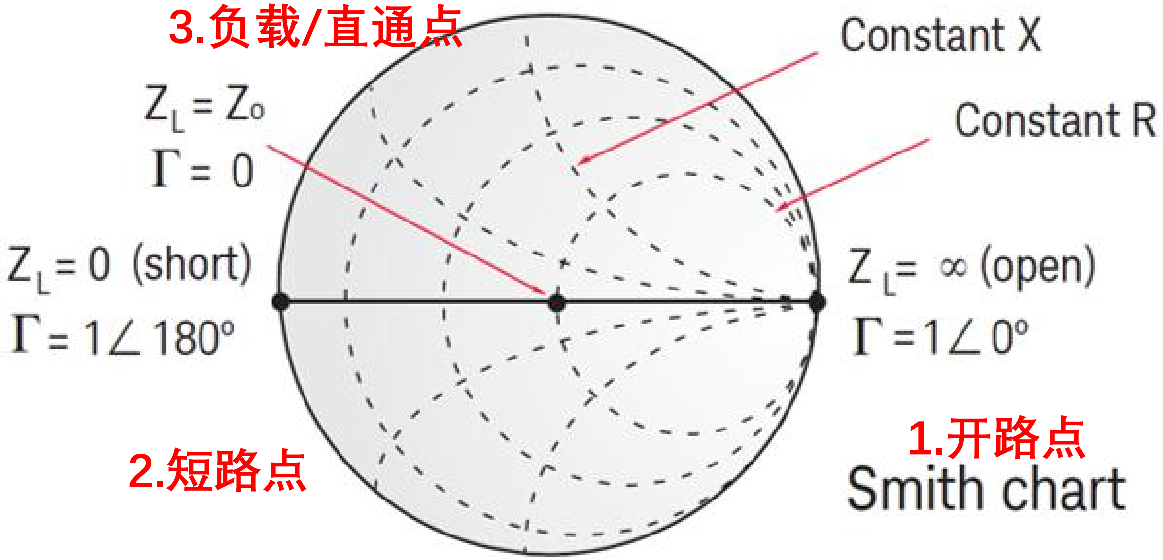
本章目录

回顾：射频阻抗的标准（1）

摄氏温标与射频阻抗的类比

摄氏温标的发明者是Anders Celsius（1701—1744），其结冰点是0℃，沸点为99.974℃。1740年瑞典人摄氏（Celsius）提出在标准大气压下，把冰水混合物的温度规定为**0度**，**水的沸腾温度规定为99.974度**。根据水这两个固定温度点来对玻璃水银温度计进行分度。两点间作100等分，每一份称为1摄氏度。记作1℃。

3.负载/直通点



2.短路点

1.开路点

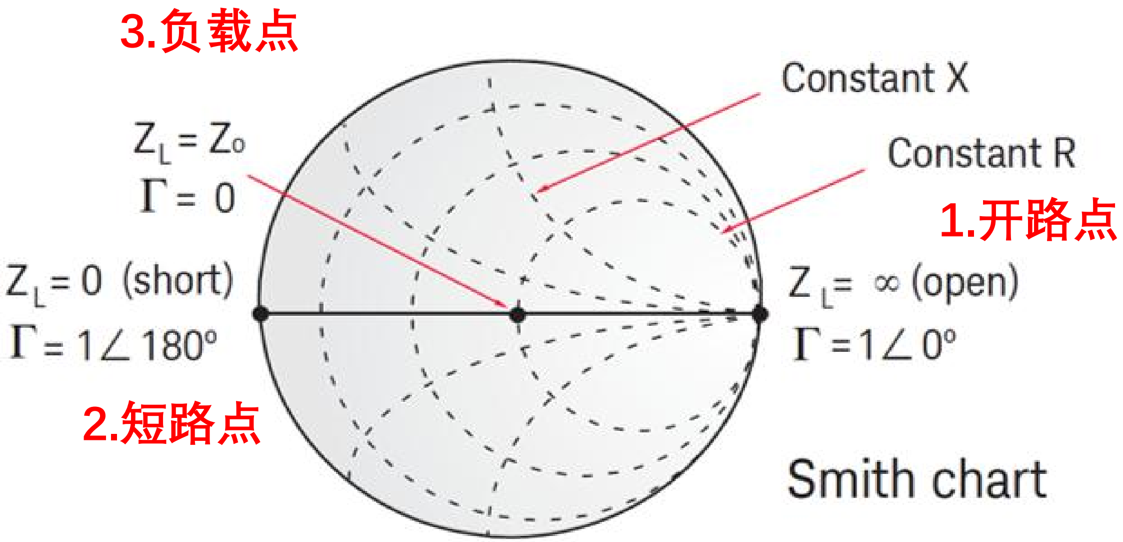
SOLT/TRL校准

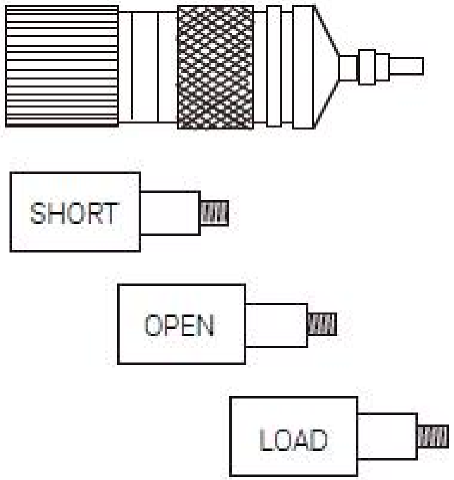
1.水的沸点

2.水的冰点

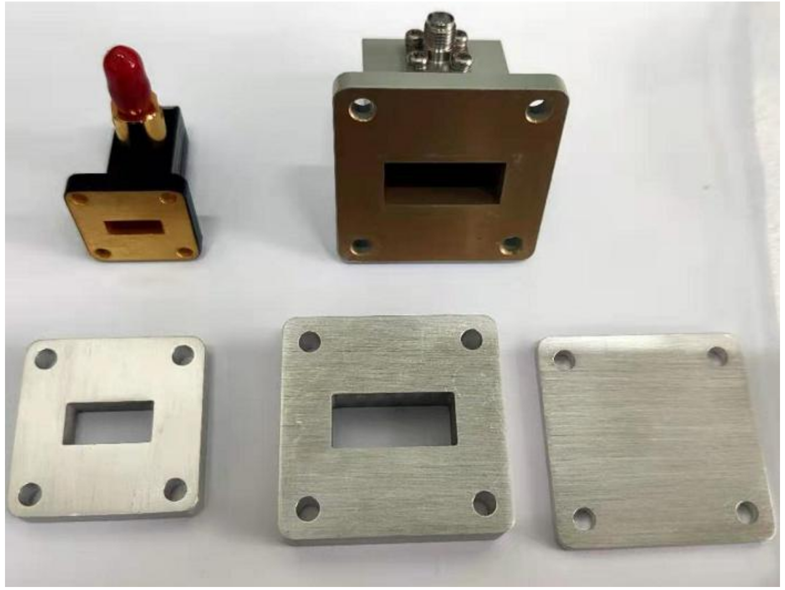
3. 标准大气压

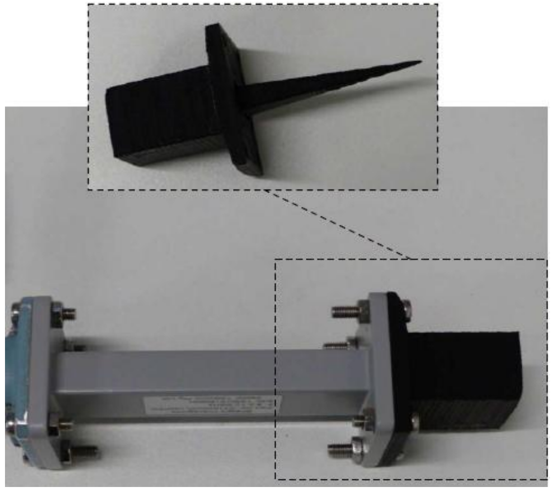
回顾：射频阻抗的标准（2）





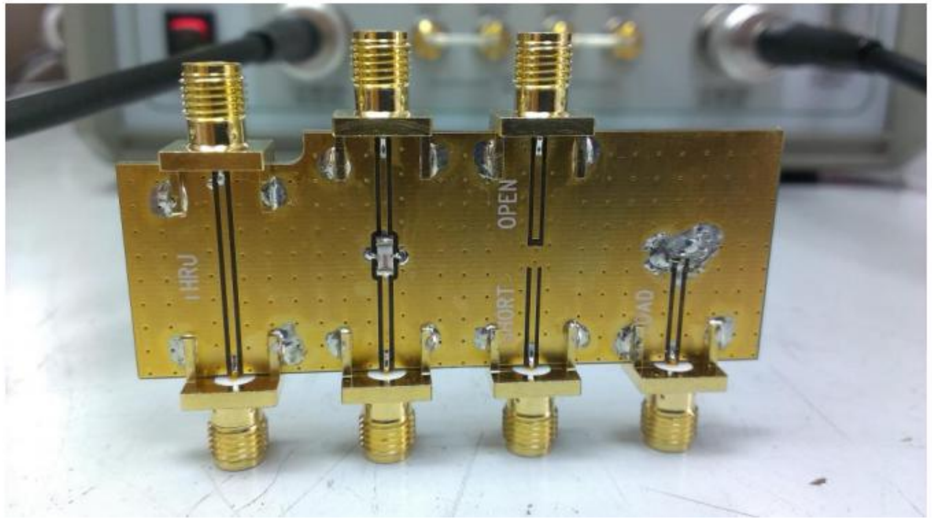
同轴标准（校准件）



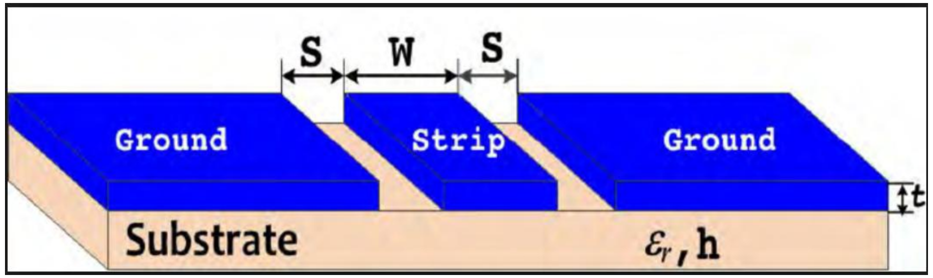


波导标准（校准件）

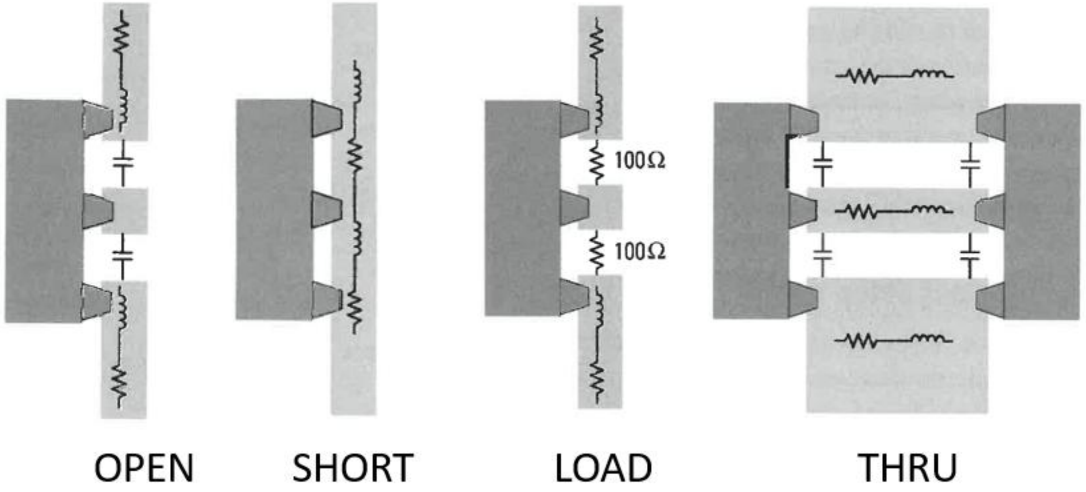
常用的低频件

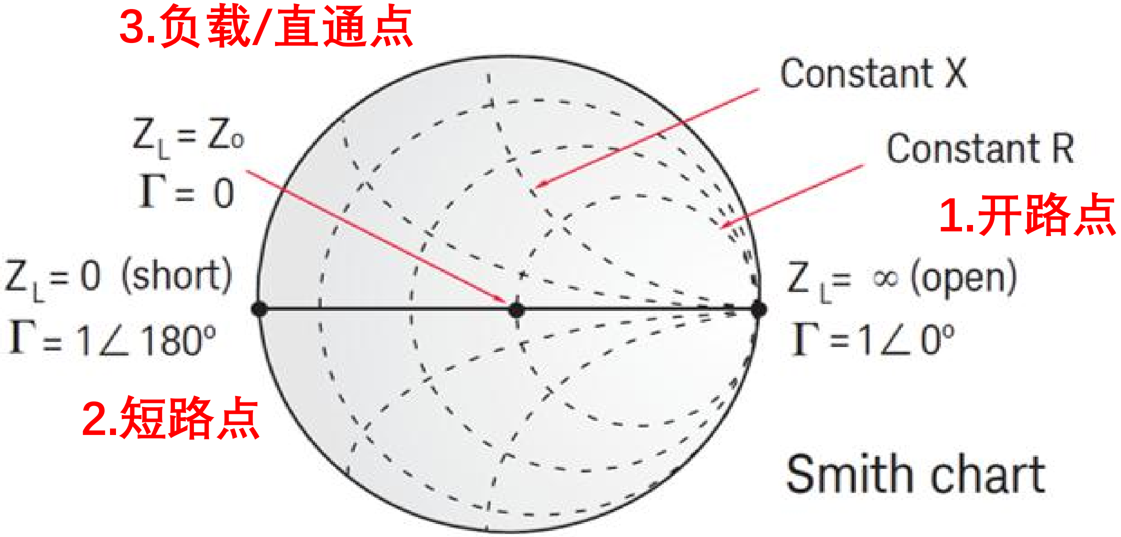


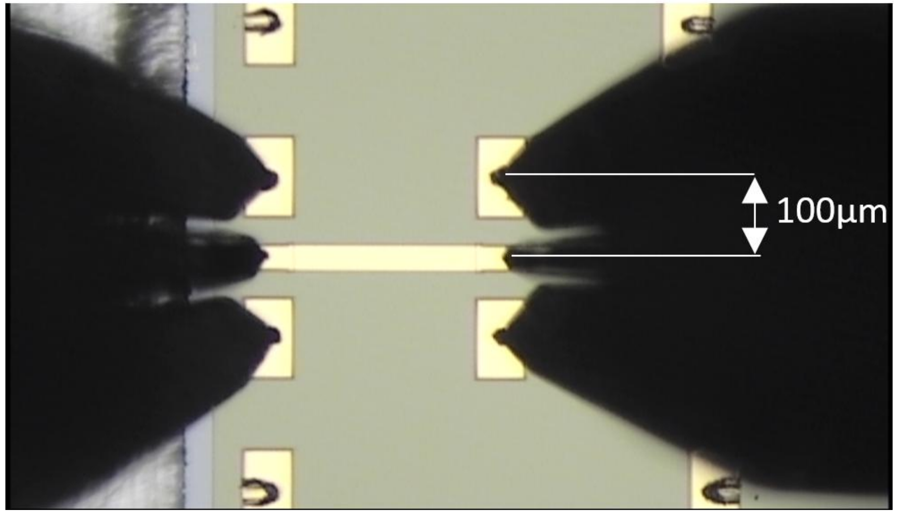
回顾：射频阻抗的标准（3）



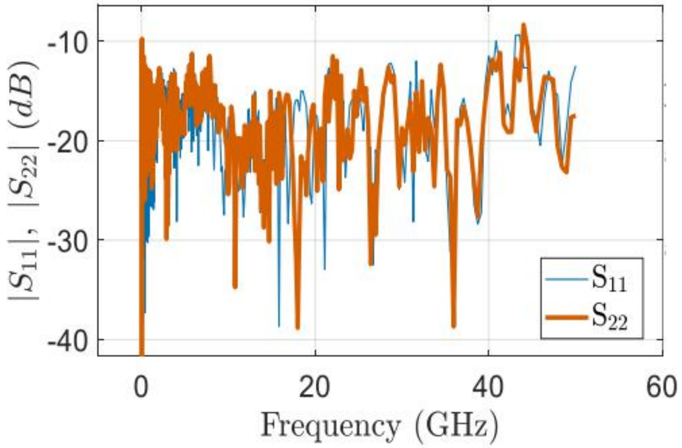
共面波导及其校准件

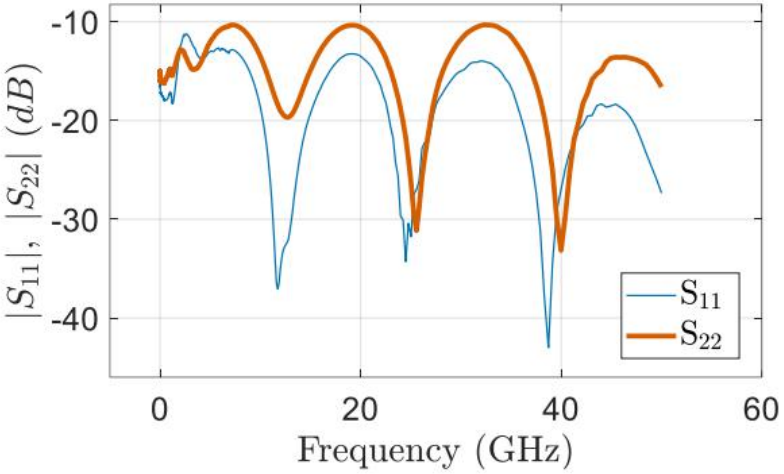




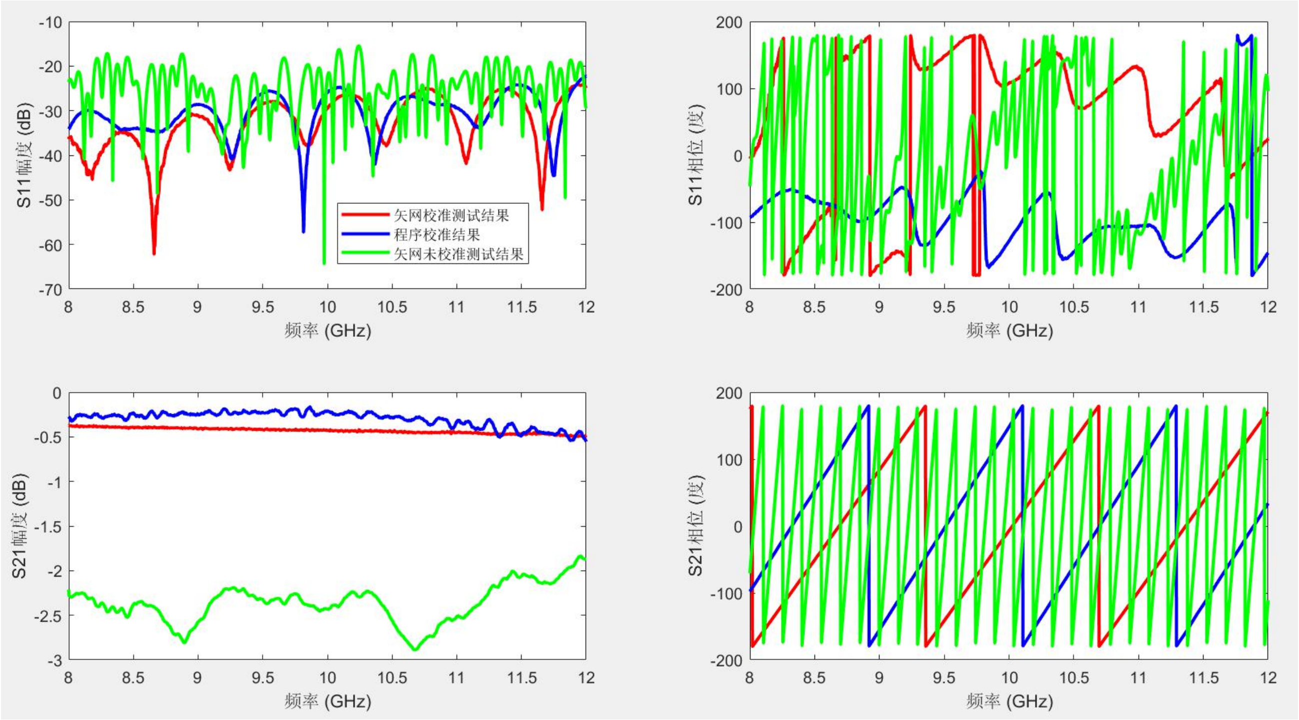


校准的意义





通常来讲，相位被“校准”之后的“效果”更加明显



校准的基本步骤：

校准通常包含**误差模型**、**校准测试**、**误差修正**三个部分

把系统中的误差部分看作一个误差网络，先针对误差网络建立误差模型，用信号流图的形式表示误差模型（列方程组）

通过测试多个**电参数已知的校准件**来确定误差模型中各个参数值（给已知条件）

通过数值计算对测试系统完成误差修正，将测试参考面从矢网测试端口移动到与待测器件的接触点（解仿真组）

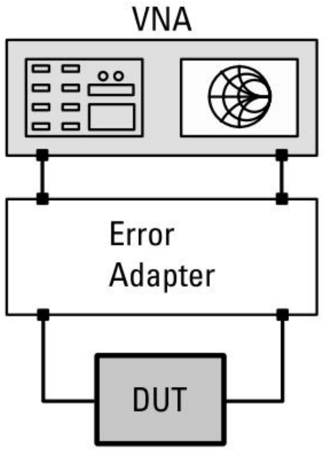


Figure 2.9 Error adapter concept used for VNA calibration.

$$\Delta S = Systematic + \sqrt{Random^2 + Drift^2}$$

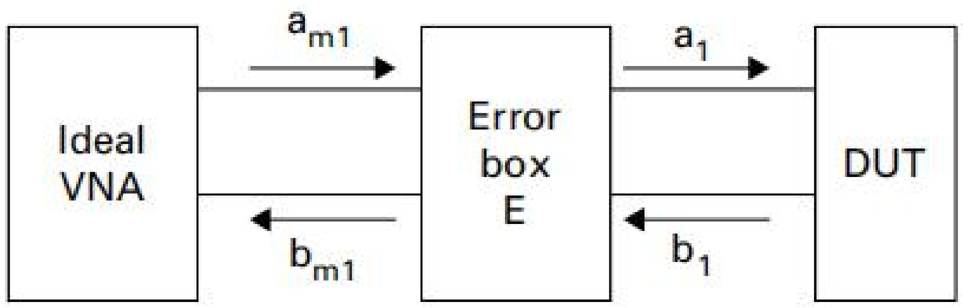
系统误差(SYSTEMATIC)：例如负载和源阻抗不匹配，有限耦合器方向性以及反射/传输功率跟踪。这些误差被认为是时不变的，并且在校准后不会改变。

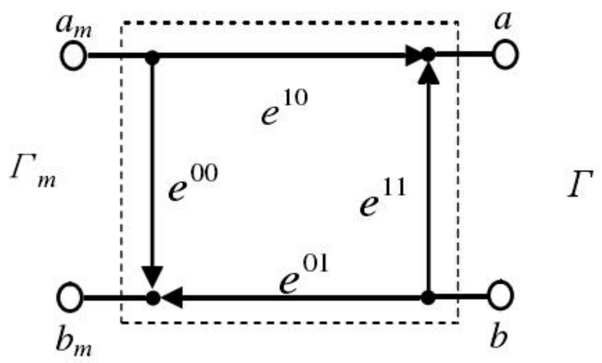
随机误差（RANDOM）：例如仪器，相位噪声以及开关和连接器的可重复性。使用平均是一种压缩随机误差影响的技术。

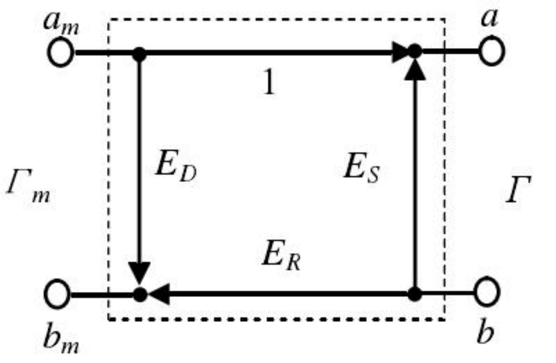
漂移或稳定性错误（DRIFT）：例如温度漂移，可以通过执行新的校准消除这些误差。

单端口误差模型

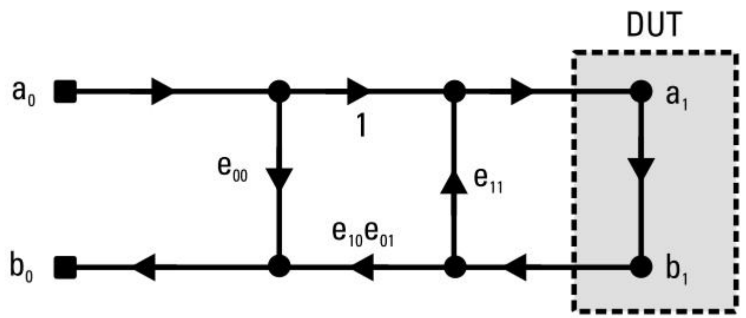
单端口反射参数测量误差模型







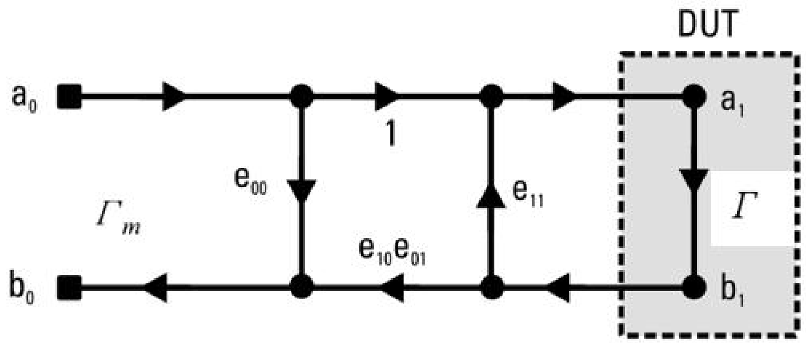
$$\Gamma_m = \frac{b_m}{a_m} = e_{00} + \frac{e_{01}e_{10}\Gamma}{1-e_{11}\Gamma}$$



$$\Gamma_m = \frac{b_m}{a_m} = e_{00} + \frac{e_{01}e_{10}\Gamma}{1-e_{11}\Gamma}$$

方向性误差e_{00}，端口匹配误差e_{11}和跟踪误差$e_{10}e_{01}$

开始列方程组:



利用开路，短路和负载作为阻抗（反射系数）的标准，求解误差参数:

（1）用一个匹配负载代替DUT进行测量，匹配负载的反射系数为0

（2）用一个短路器代替DUT进行测量，短路器的反射系数为-1

（3）用一个开路器代替DUT进行测量，短路器的反射系数为1

$$\Gamma_m = \frac{b_m}{a_m} = e_{00} + \frac{e_{01}e_{10}\Gamma}{1-e_{11}\Gamma}$$

$$e_{00} + \Gamma_1\Gamma_{m1}e_{11} - \Gamma_1\left(e_{00}e_1 - e_{01}e_{10}\right) = \Gamma_{m1}$$

$$e_{00} + \Gamma_2\Gamma_{m2}e_{11} - \Gamma_2\left(e_{00}e_1 - e_{01}e_{10}\right) = \Gamma_{m2}$$

$$e_{00} + \Gamma_3\Gamma_{m3}e_{11} - \Gamma_3\left(e_{00}e_1 - e_{01}e_{10}\right) = \Gamma_{m3}$$

$$\Gamma_m = \frac{b_0}{a_0} = \frac{e_{00} - \Delta e\Gamma}{1-e_{11}\Gamma}$$

$$\Gamma = \frac{b_1}{a_1} = \frac{\Gamma_m - e_{00}}{\Gamma_m e_{11} - \Delta e}$$

$$\Delta e = e_{00}e_{11} - e_{01}e_{10}$$

$$E_D + \Gamma_1\Gamma_{m1}E_S - \Gamma_1\left(E_DE_S - E_R\right) = \Gamma_{m1}$$

$$E_D + \Gamma_2\Gamma_{m2}E_S - \Gamma_2\left(E_DE_S - E_R\right) = \Gamma_{m2}$$

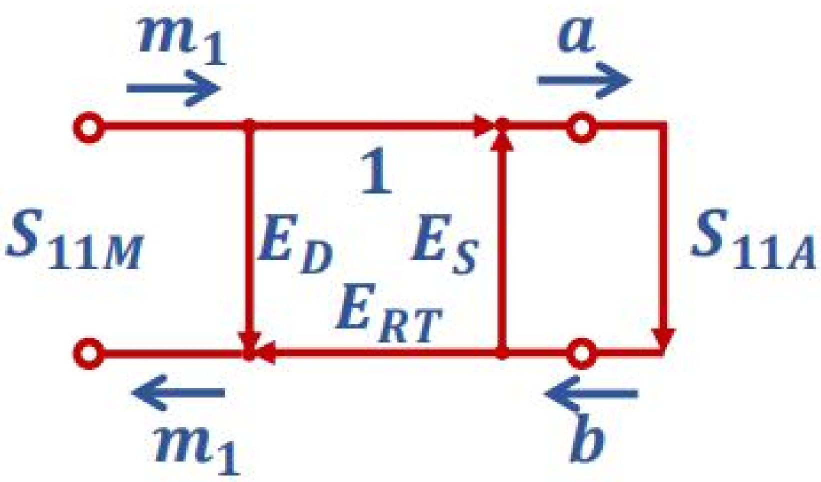
$$E_D + \Gamma_3\Gamma_{m3}E_S - \Gamma_3\left(E_DE_S - E_R\right) = \Gamma_{m3}$$

思考:
标准是什么？ （谁是秤砣）
什么是秤杆？

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

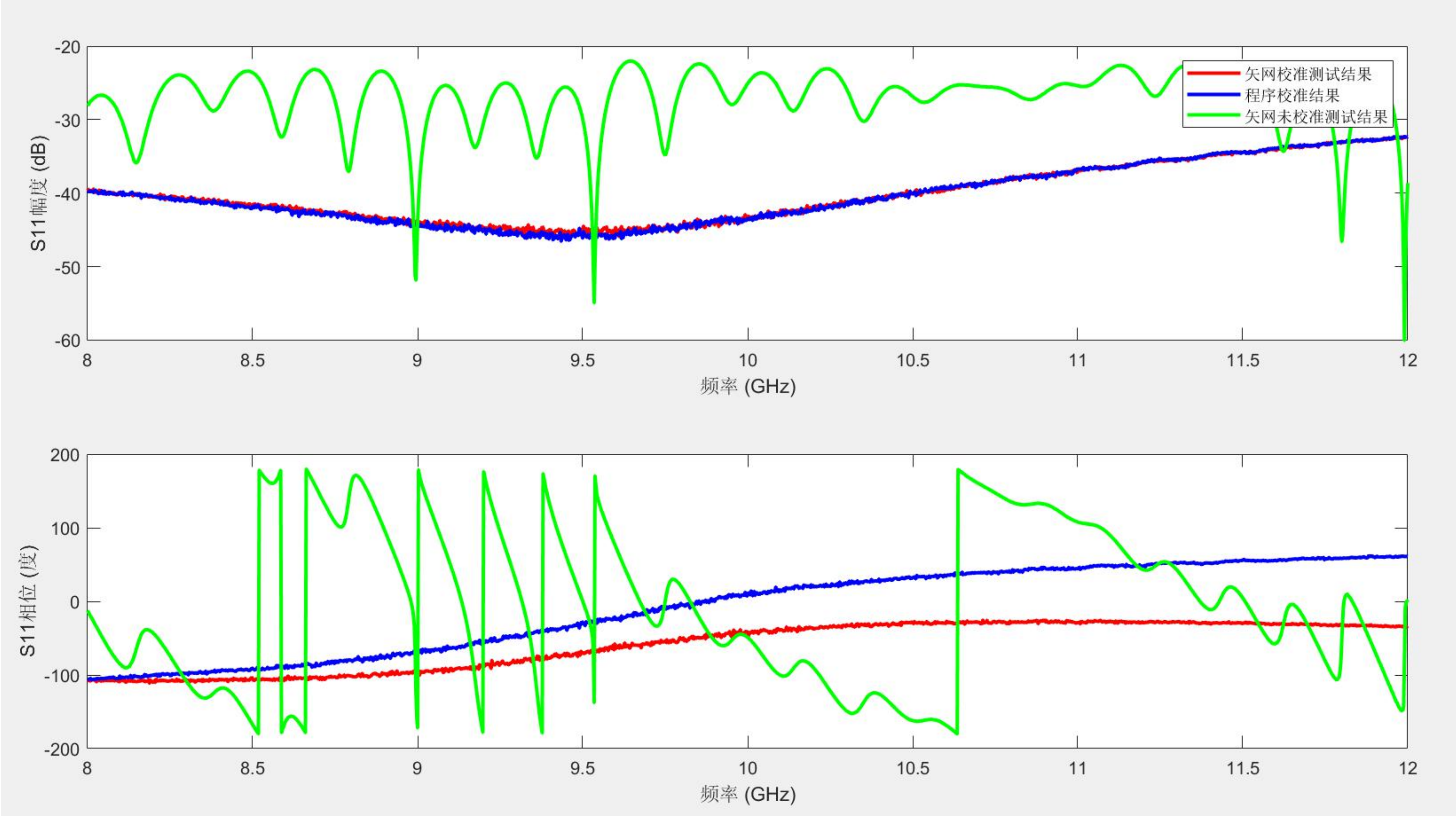
常用校准件:

- short
- open
- load

Port 1 的 E_D，E_S，E_{RT}

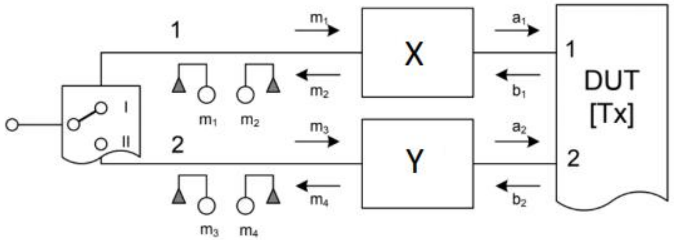
Port 2 的 E'_D，E'_S，E'_{RT}

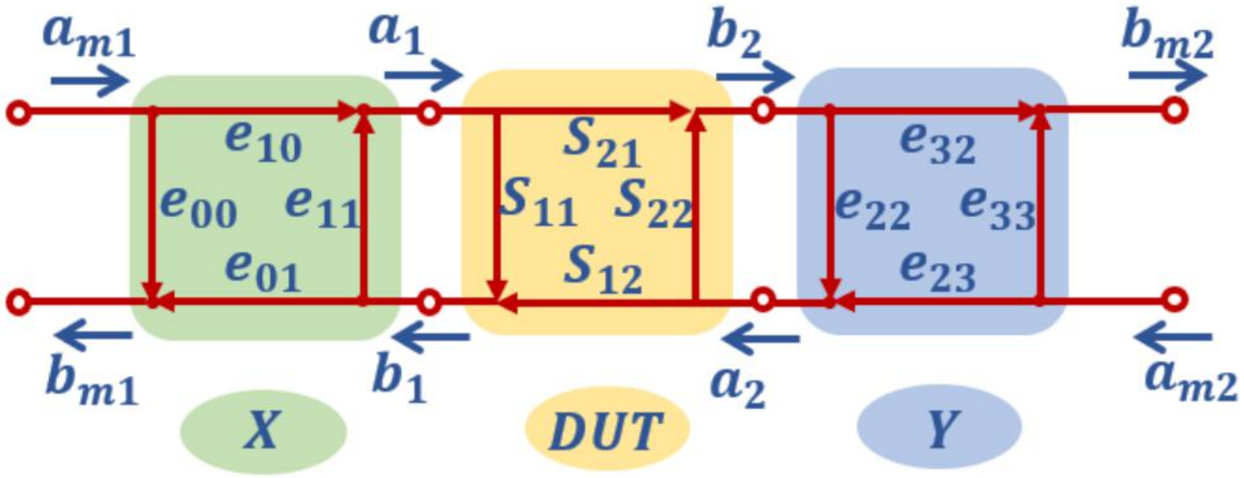
校准方法：单端口SOL 误差模型：三项误差模型 器件：负载



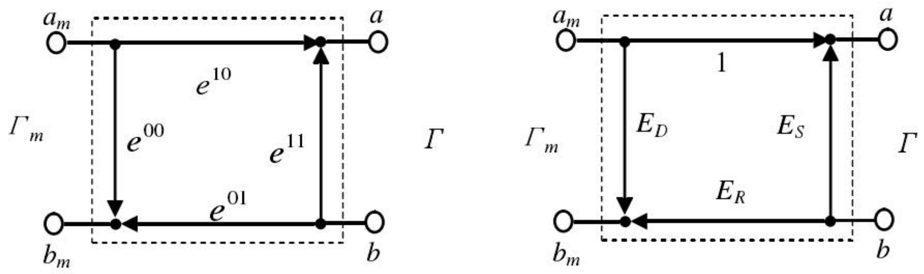
双端口误差模型（1）：突然画风变复杂，但是原理差不多

8相误差模型

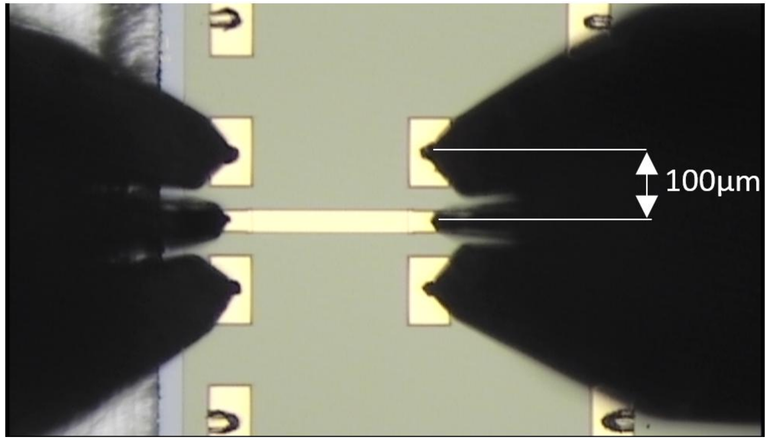




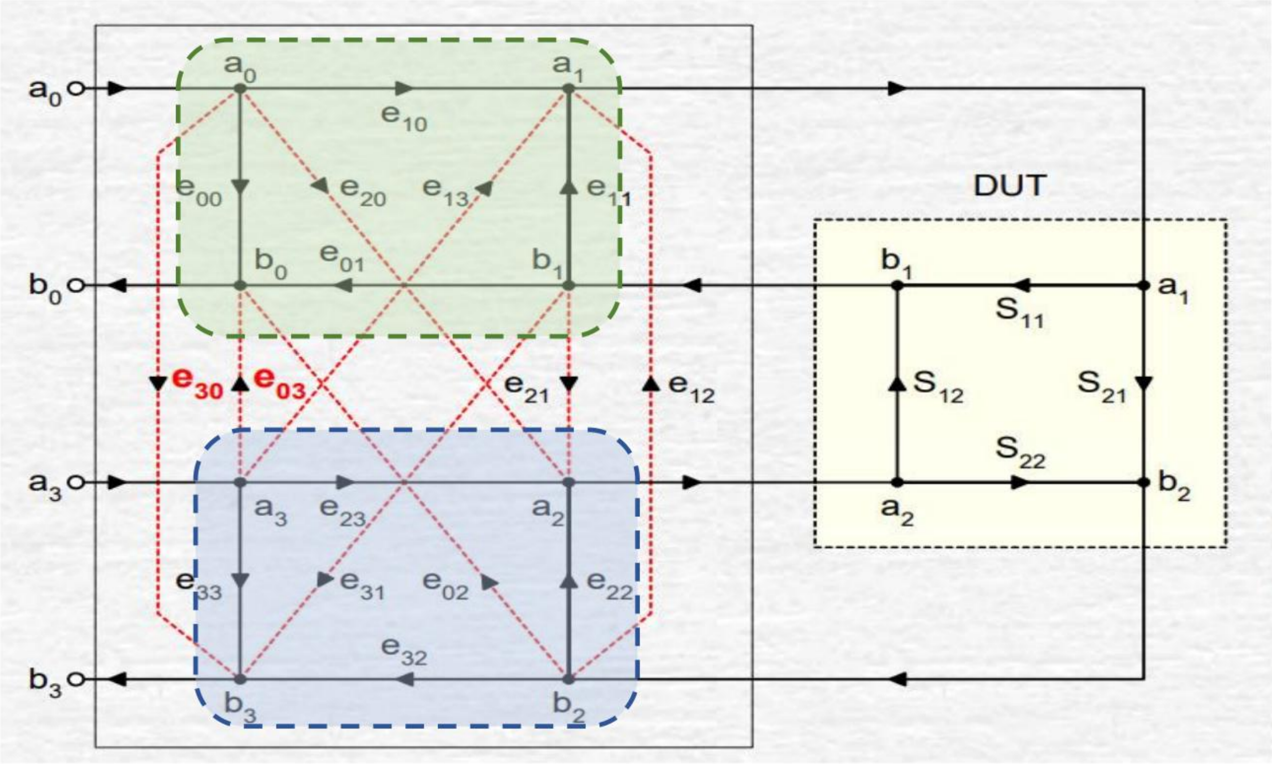
单端口反射参数测量误差模型



双端口误差模型（2）：考虑设备本身的串扰



16(15)相误差模型

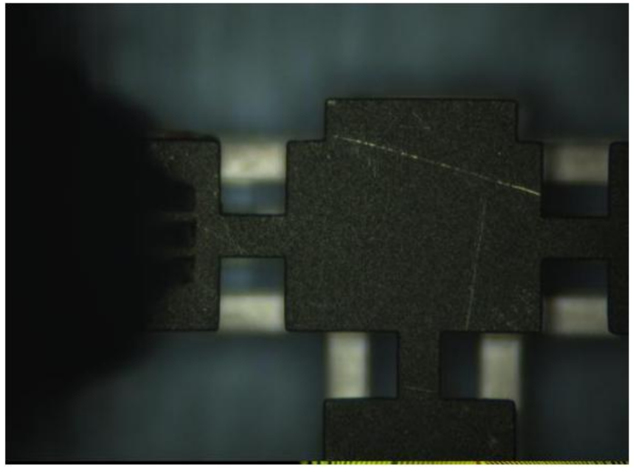


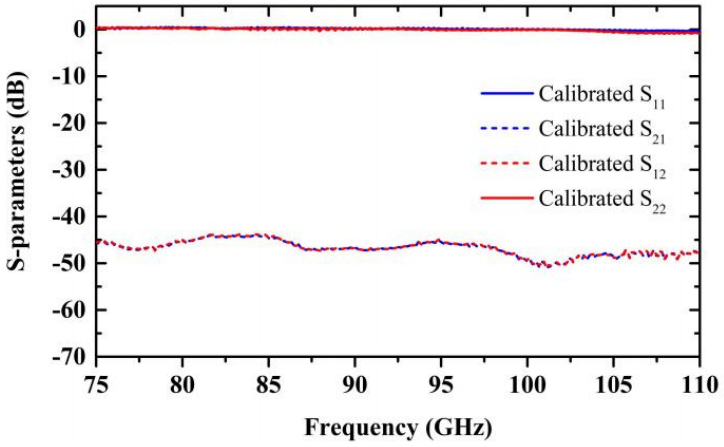
若只考虑e_{03}和e_{30}，
是10相误差模型

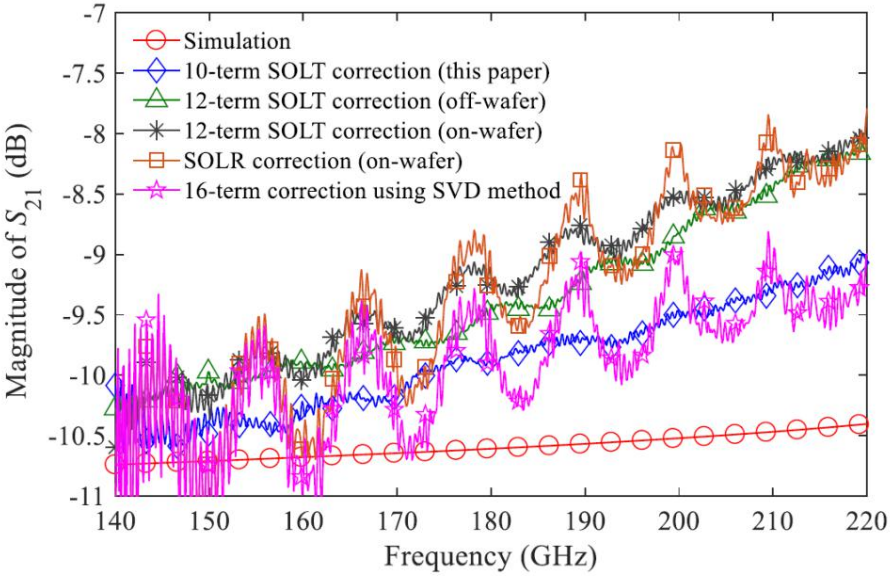
e_{00}, e_{33} Directivity
e_{11}, e_{22} Port Match
e_{10}, e_{01}, e_{32}, e_{23} Tracking
e_{30}, e_{03} Primary Leakage

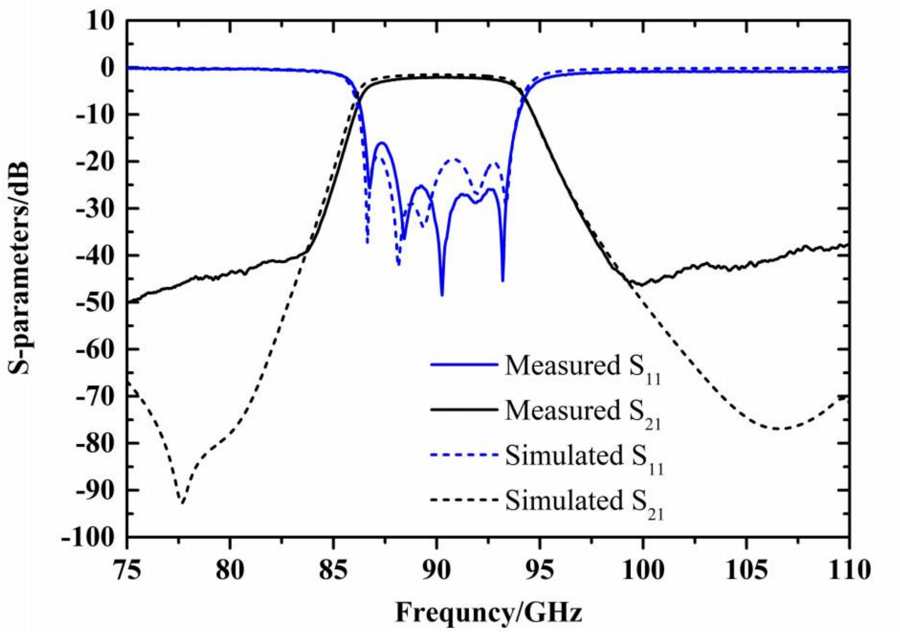
All others are lower level leakage paths

例：串扰对测试结果的影响









12相误差模型

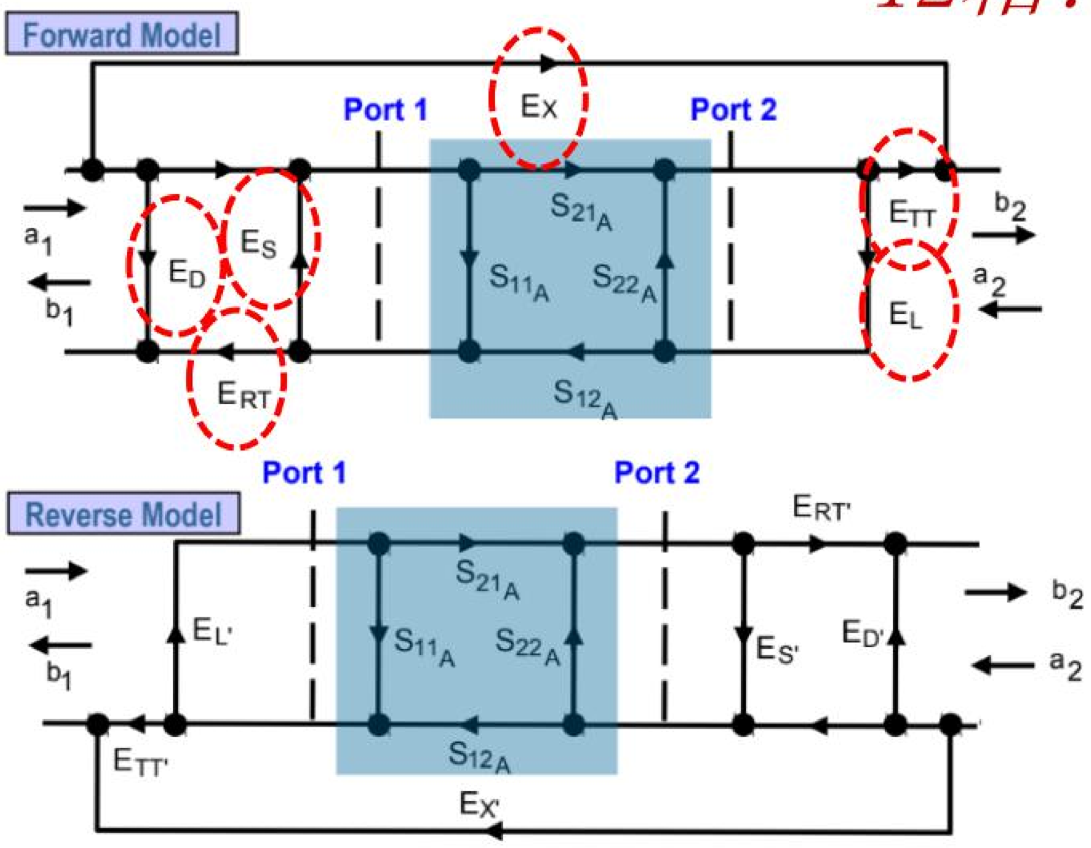
12相!

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

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

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

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



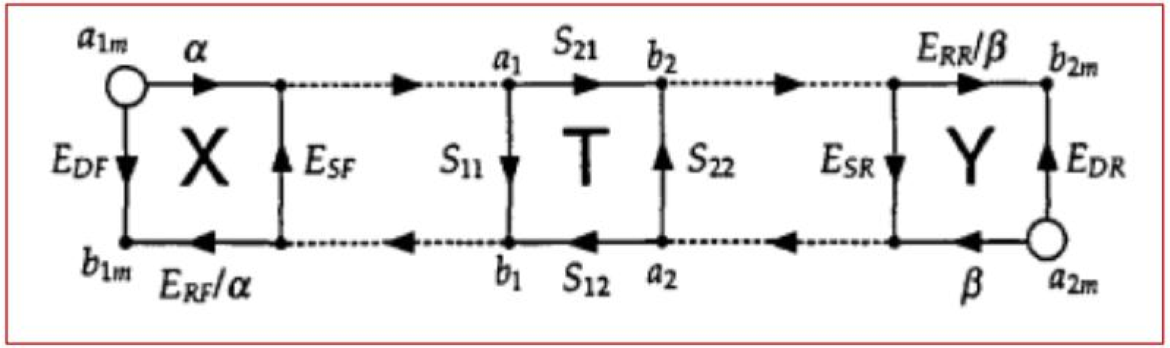
E_D = fwd directivity
E_S = fwd source match
E_{RT} = fwd reflection tracking
$E_{D'}$ = rev directivity
$E_{S'}$ = rev source match
$E_{RT'}$ = rev reflection tracking

E_L = fwd load match
E_{TT} = fwd transmission tracking
E_X = fwd isolation
$E_{L'}$ = rev load match
$E_{TT'}$ = rev transmission tracking
$E_{X'}$ = rev isolation

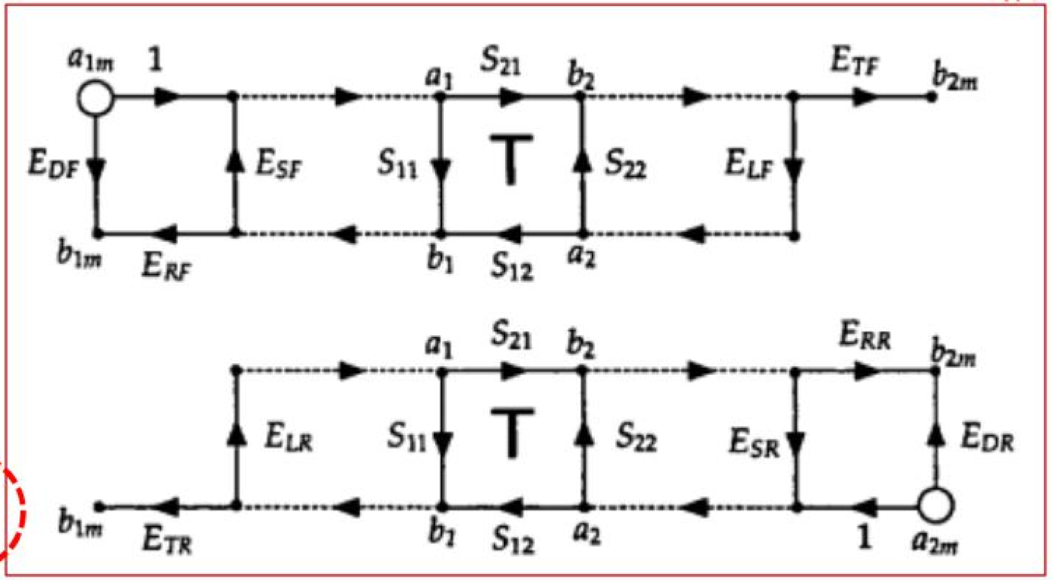
4个校准后的S参数是测量S参数的函数

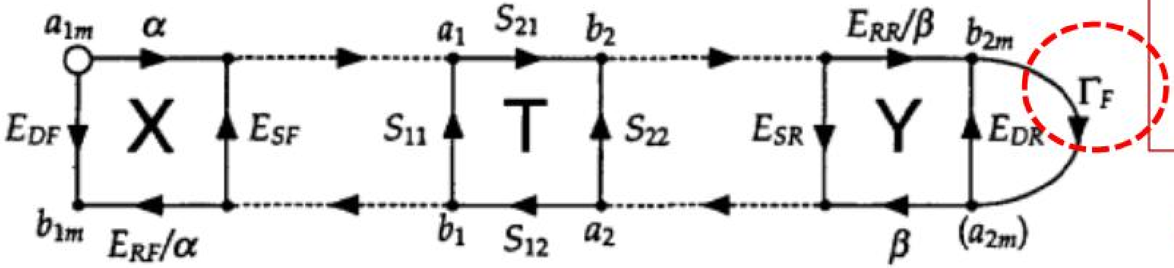
12相与8相误差模型间的联系

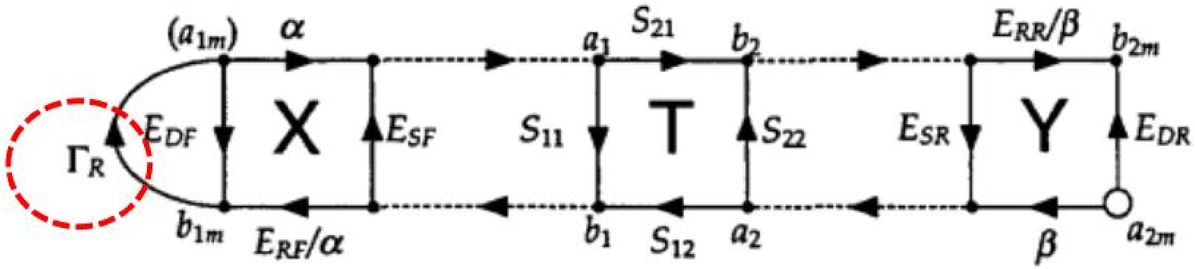
8相



10相



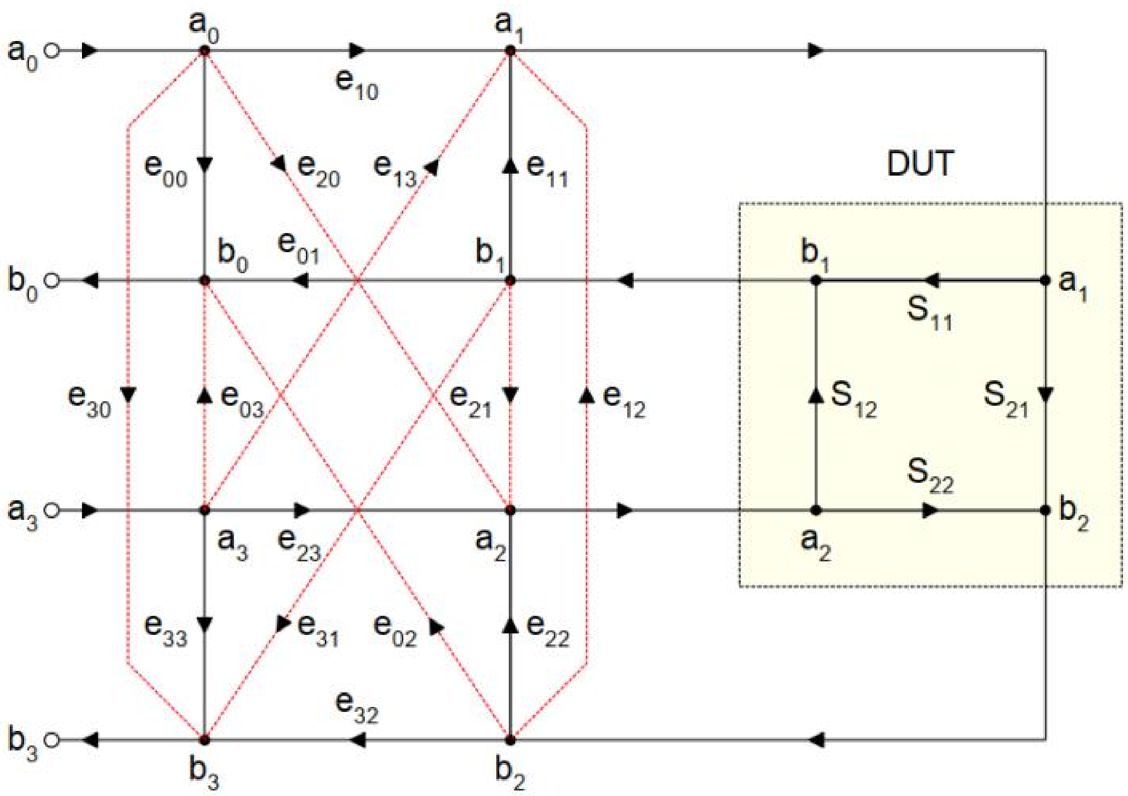


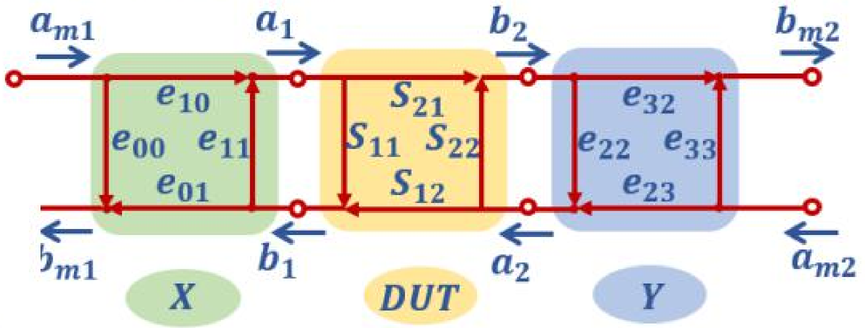


Γ_F和Γ_R: switch terms

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

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

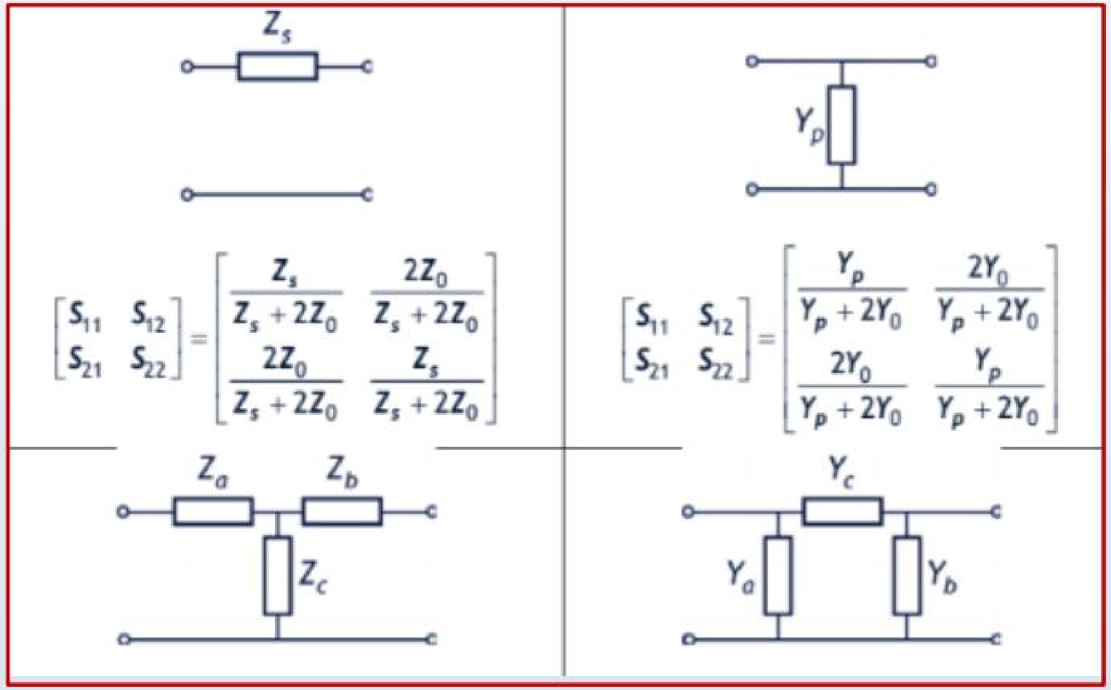
$$\begin{bmatrix} b_0 \\ b_3 \\ \hline a_0 \\ a_3 \end{bmatrix} = \left[\begin{array}{c|c} \mathbf{T}_1 & \mathbf{T}_2 \\ \hline \mathbf{T}_3 & \mathbf{T}_4 \end{array}\right] \begin{bmatrix} b_1 \\ b_2 \\ \hline a_1 \\ a_2 \end{bmatrix}$$

误差模型与校准件数量？

误差模型	求解未知量	需要已知量	校准件数量
12相模型	10组	≥ 10组	
8相模型	7组	≥ 7组	
16相模型	15组	≥ 15组	

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**



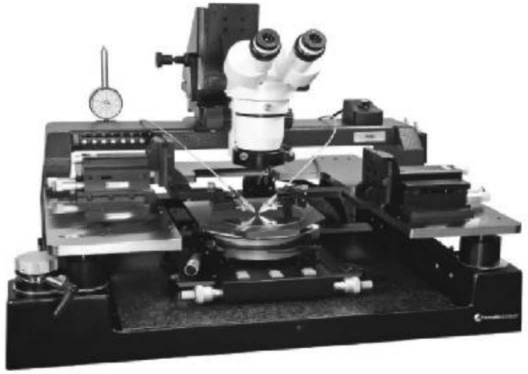
校准算法小结

1. 校准通常包含**误差模型**、**校准测试**、**误差修正**三个部分；
2. Thru， open， short， load 等校准件是射频阻抗的标准；
3. 通过校准测试和误差模型， 可以将标准映射到DUT
4. 校准的过程类似联立方程组解方程， 要特别注意方程未知数的个数和测量次数的对应关系。
5. 最简单的双端口误差模型为8（7）项误差模型。最复杂的为16（15）项误差模型
6. 更多细节可以参考鲍秀娥老师的PPT。

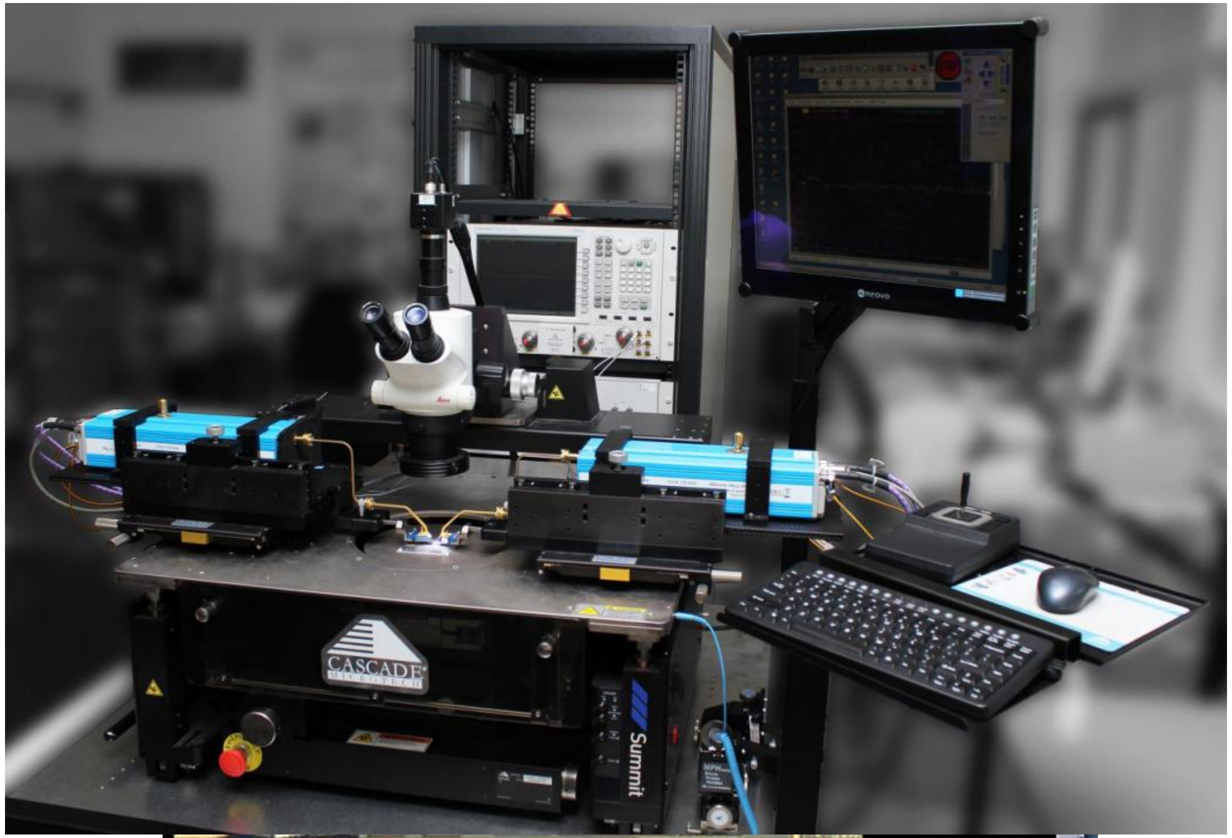
本章目录

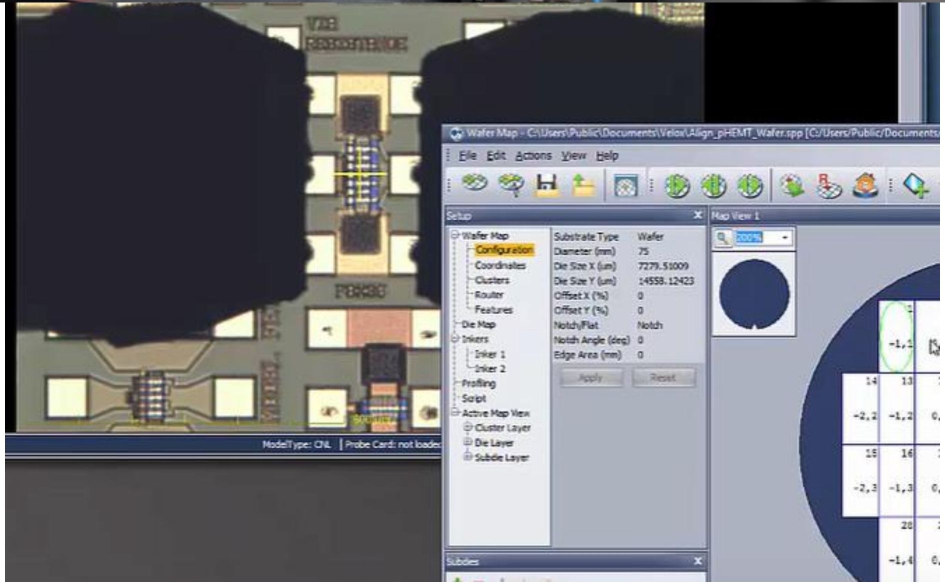
探针台：手动和自动

(a)



(b)





探针台：组成部分

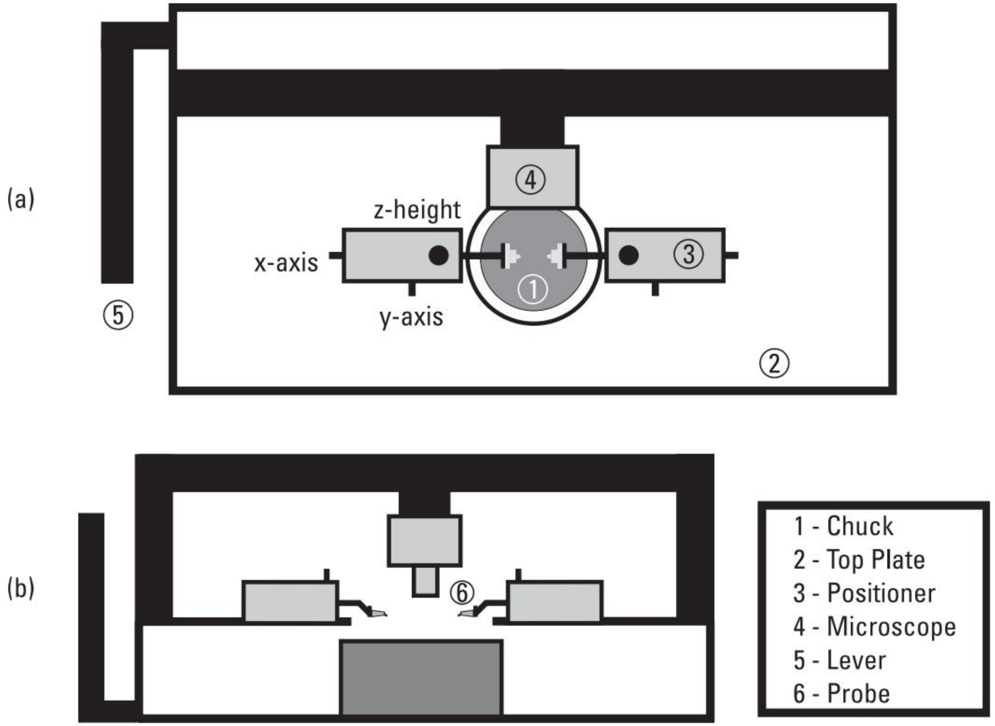
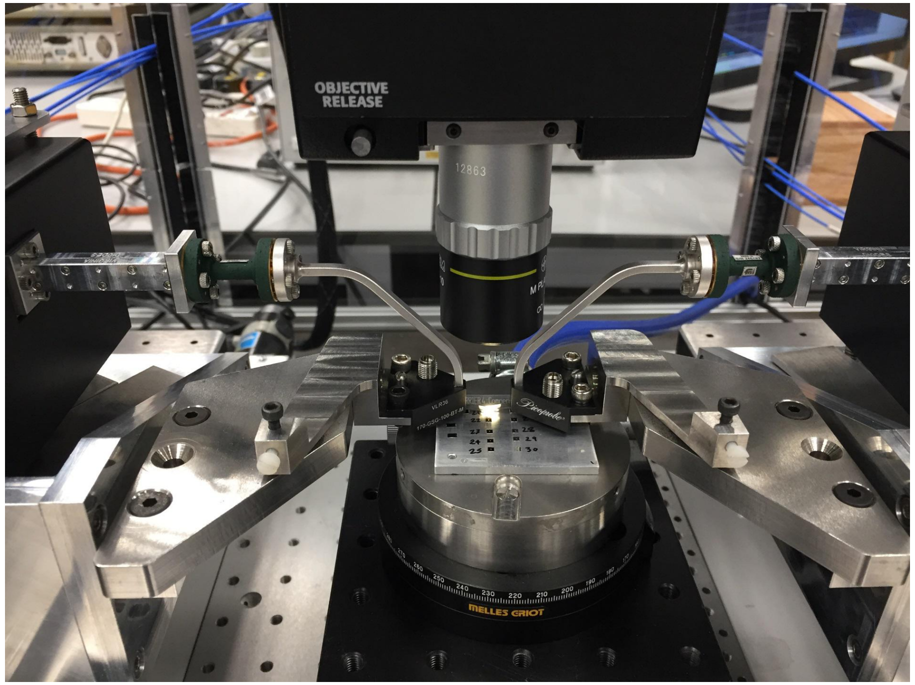
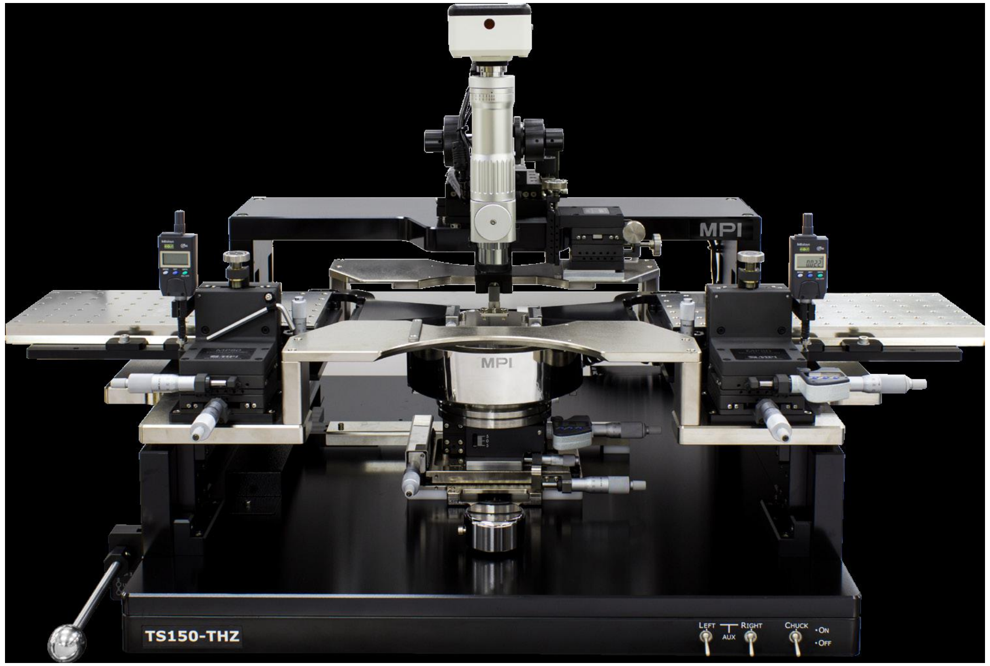


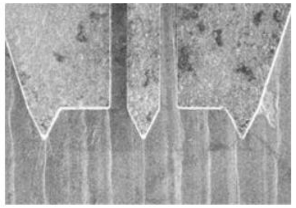
Figure 1.1 (a) Top view, (b) Front view. Manual probe station and its core building blocks.



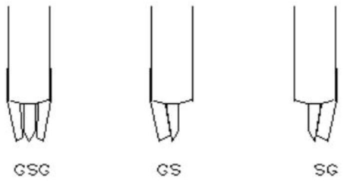


探针台：GSG探针

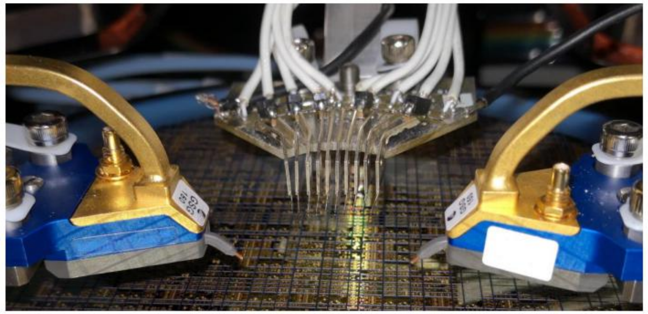
转换头：探针



Top View



GSG, SG, GS, GSGSG, GSSG, SGS等



液晶(LCP)，镀镍，非氧化镍合金

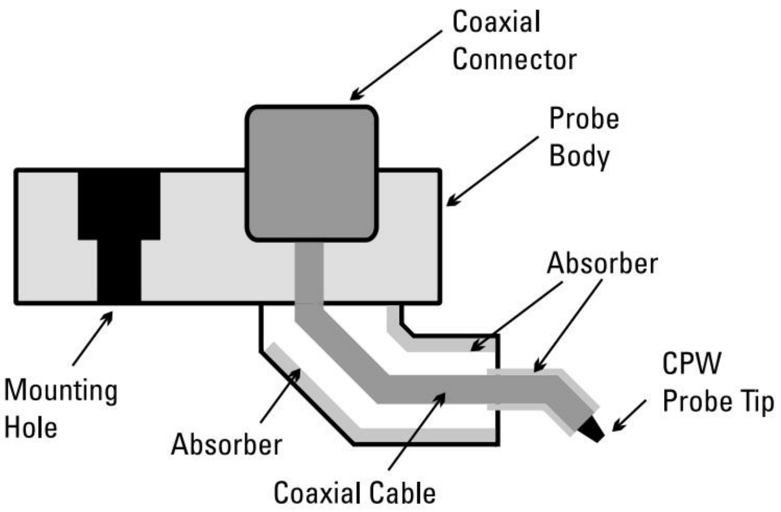
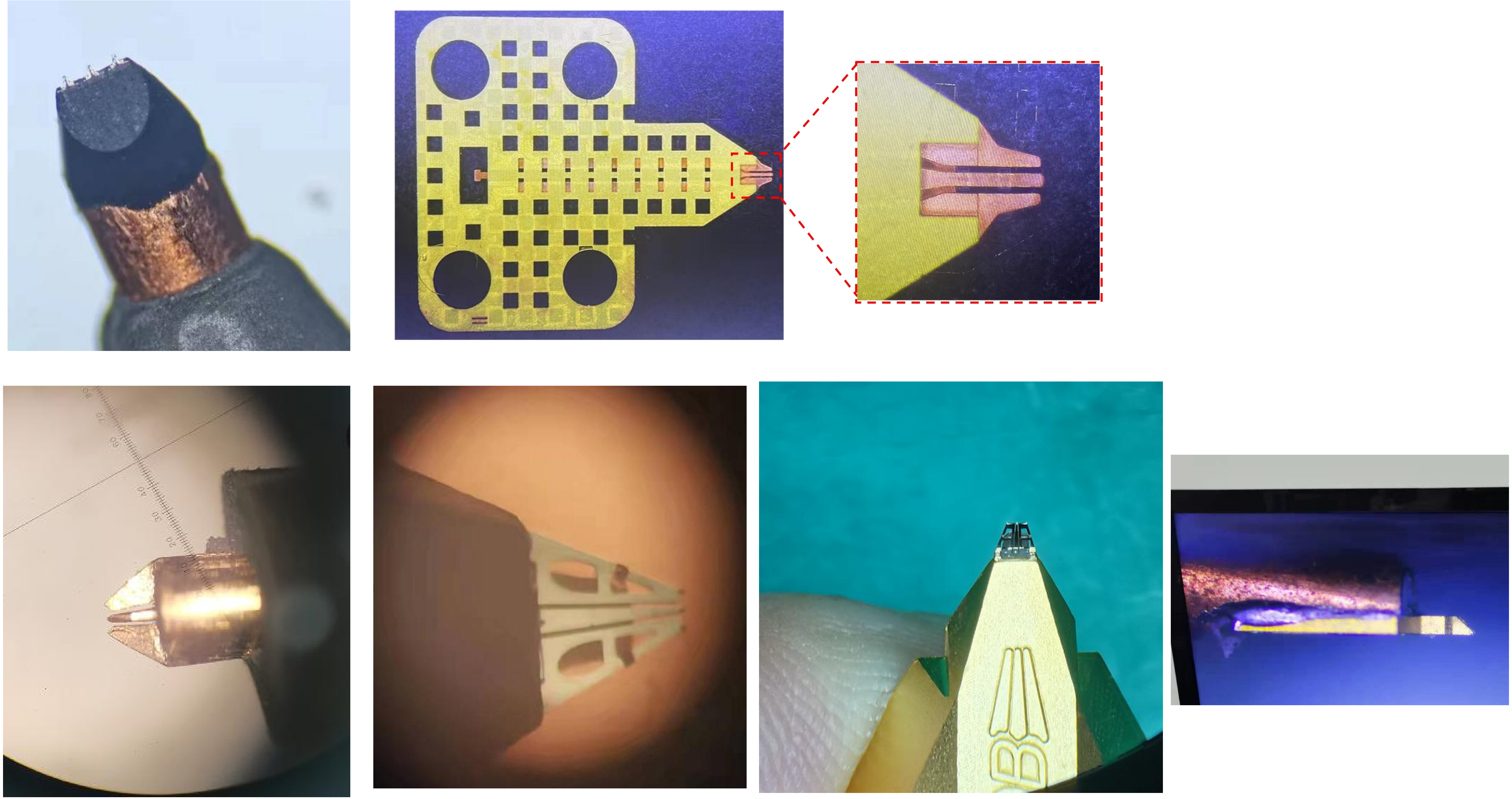


Figure 1.4 On-wafer RF probe.



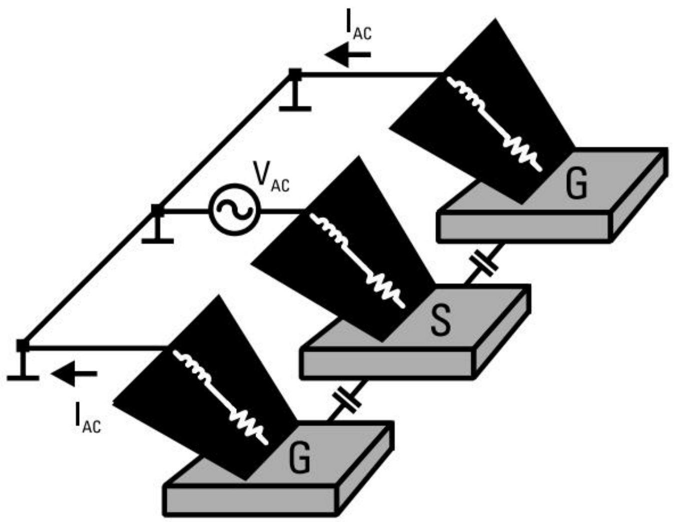


Figure 1.7 Signal excitation at coplanar GSG probe tips.

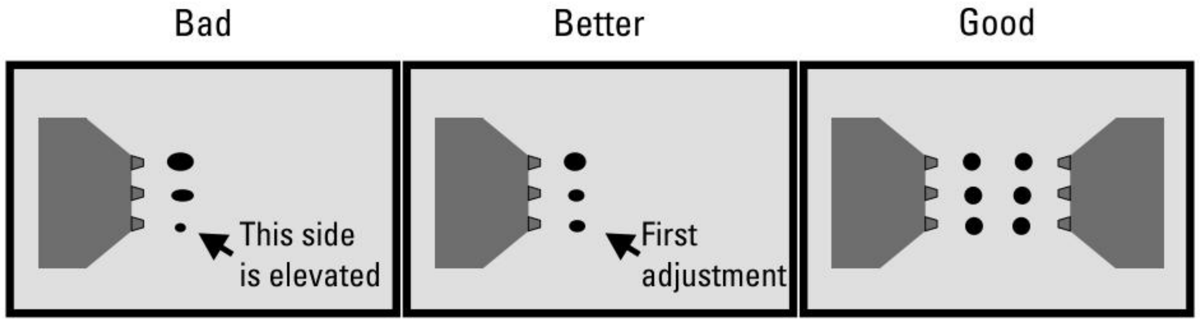
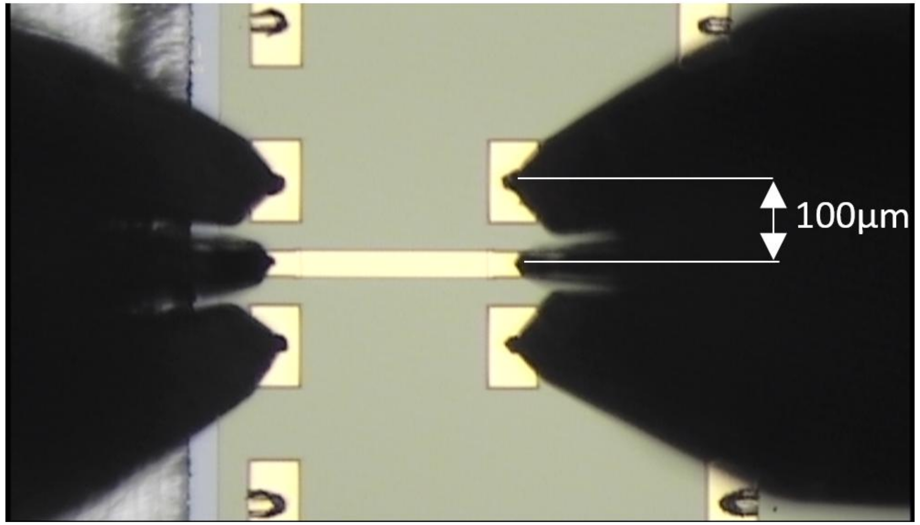
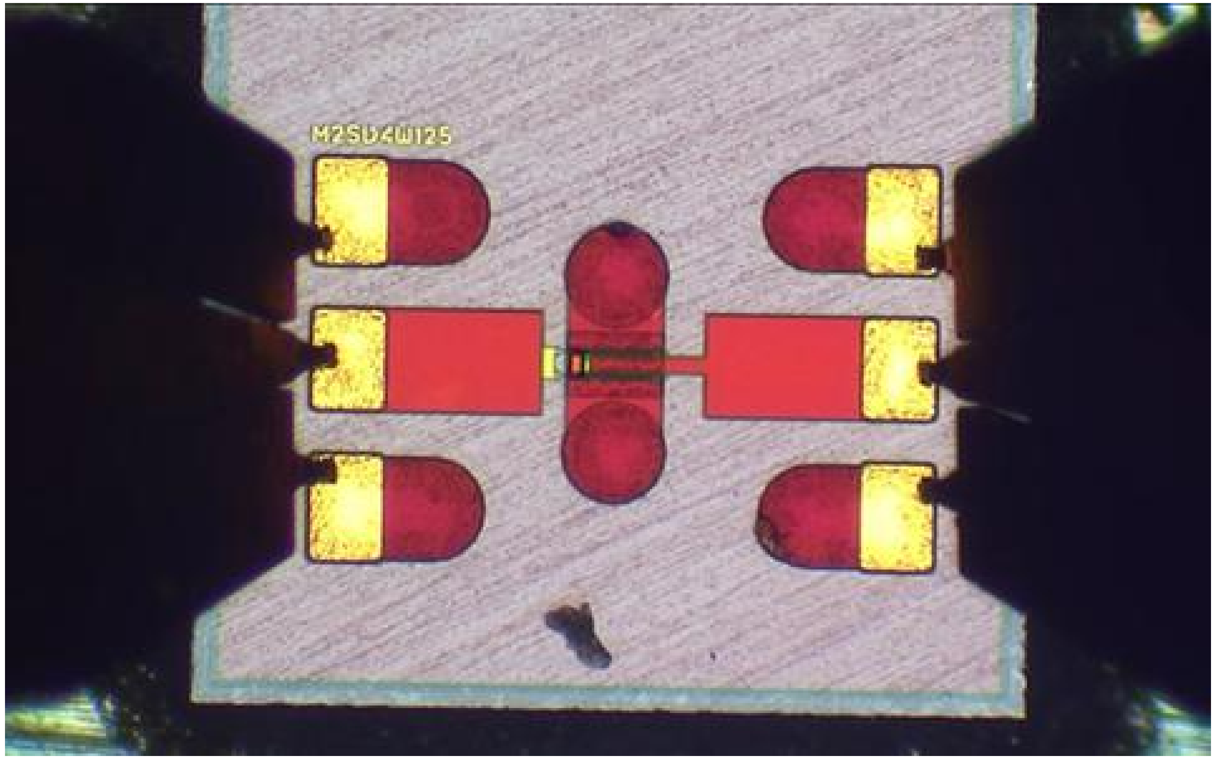
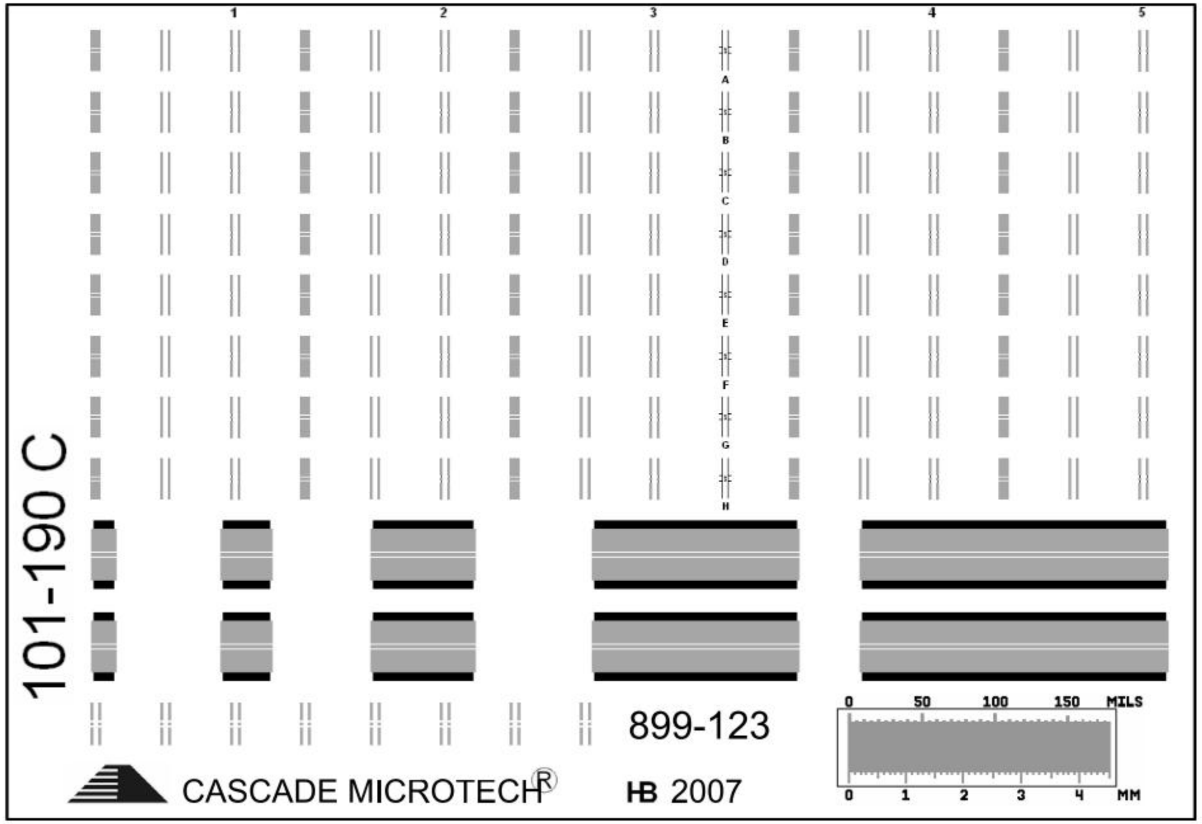


Figure 1.8 Planarization of probe tips on contact substrate.

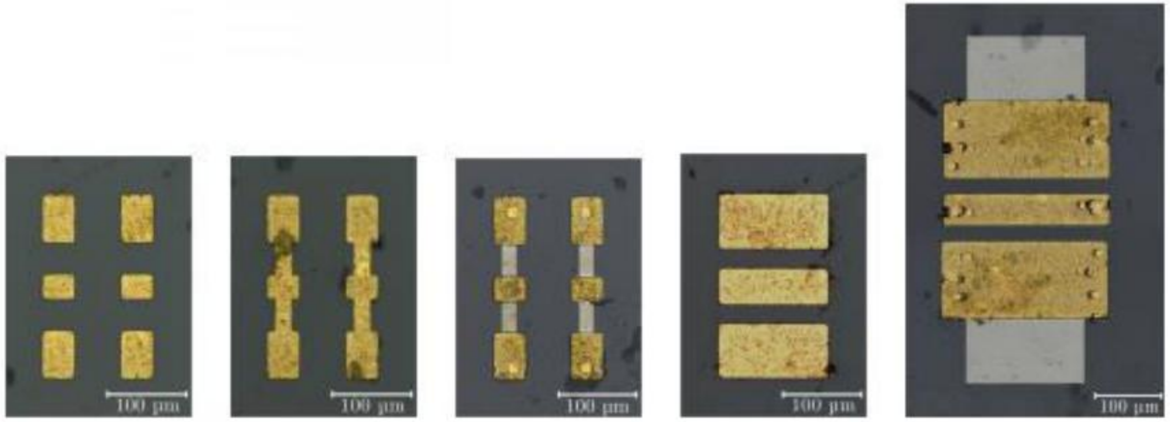




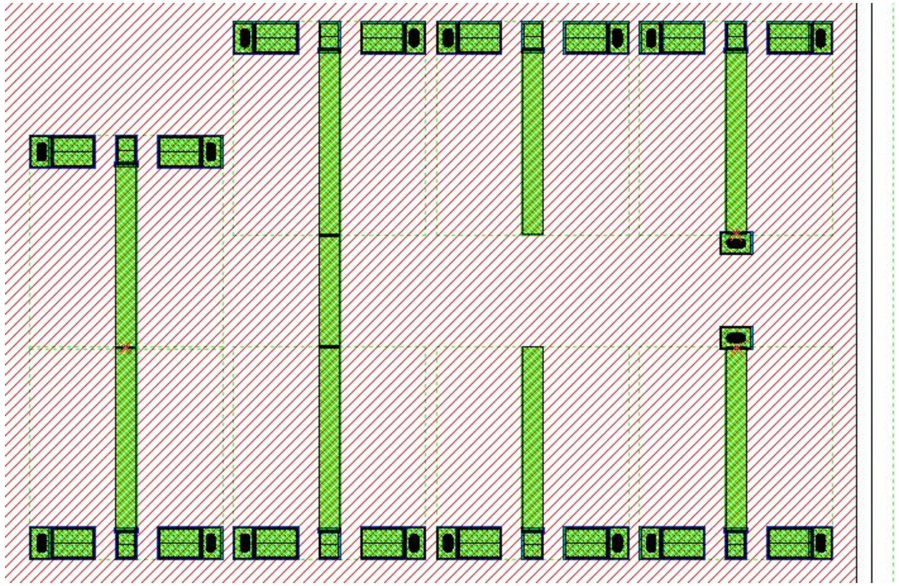
探针台：校准件（商业校准片）

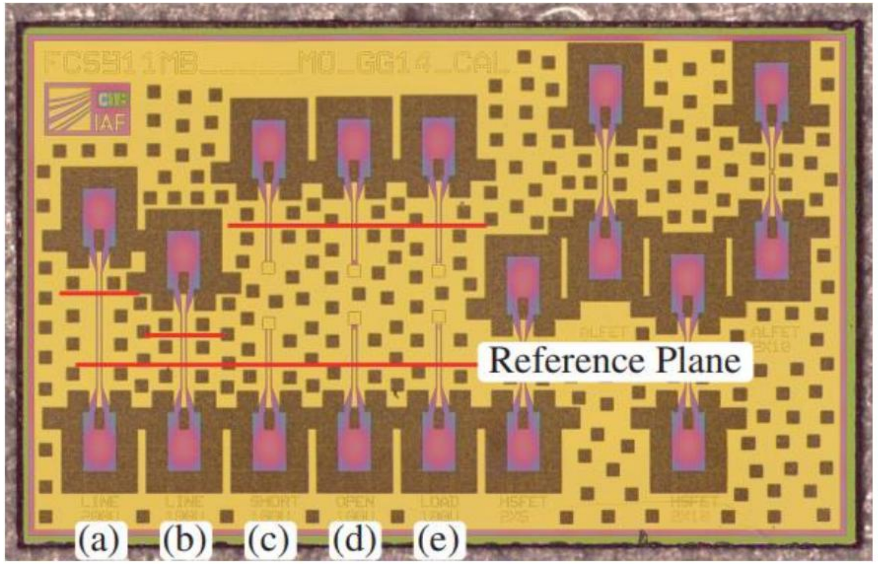


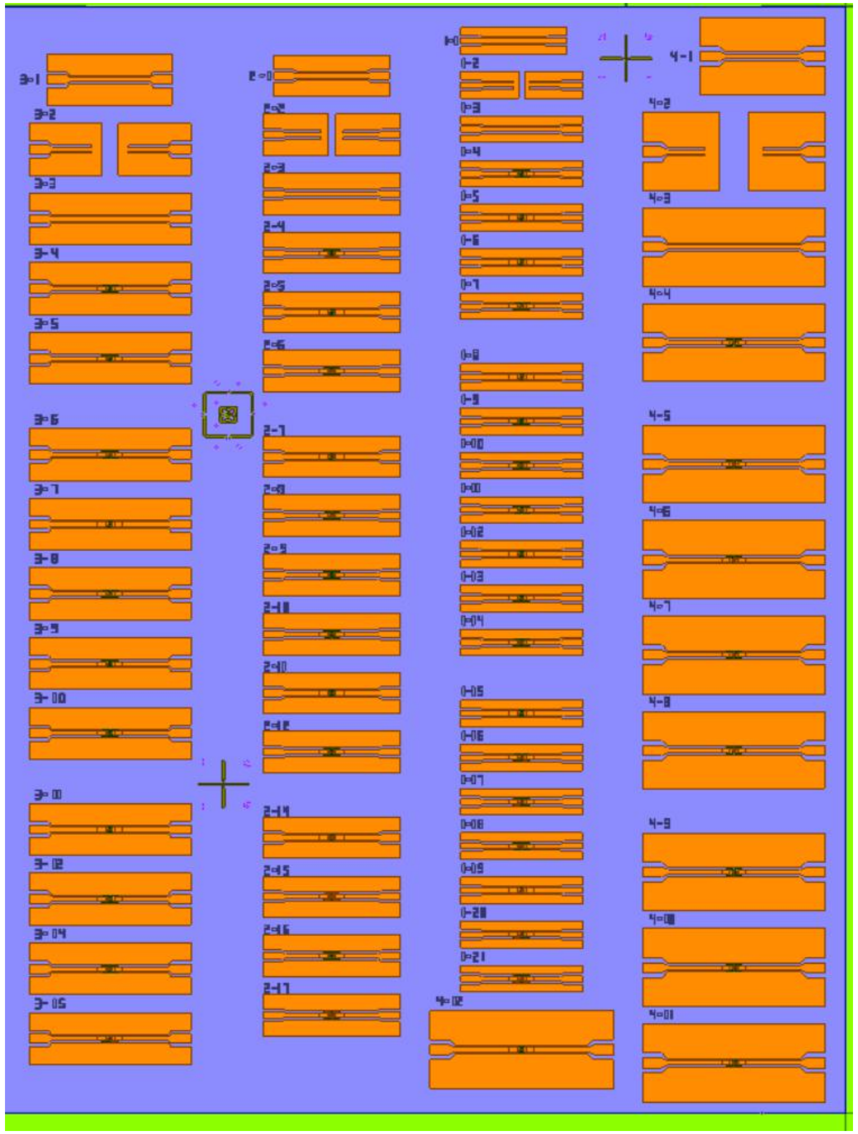
igure 1.13 Calibration substrate. (Courtesy of Cascade Microtech, Inc.)

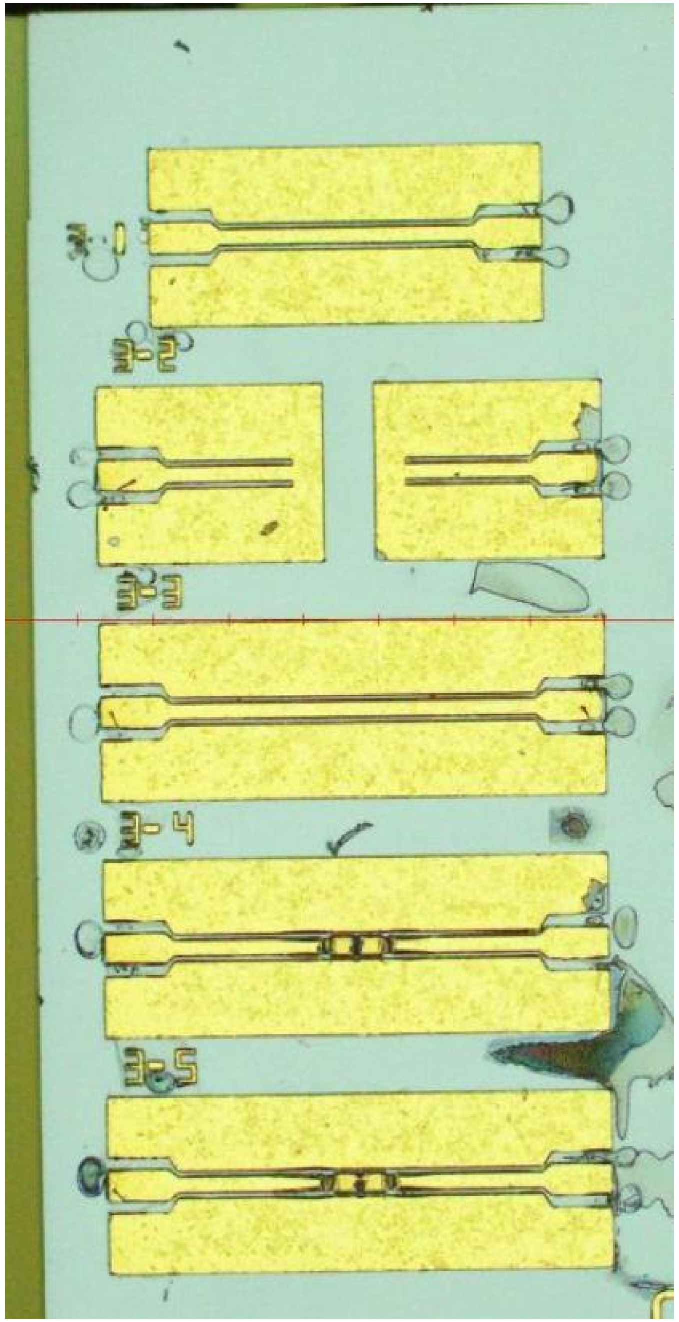


探针台：校准件（自定义校准件）



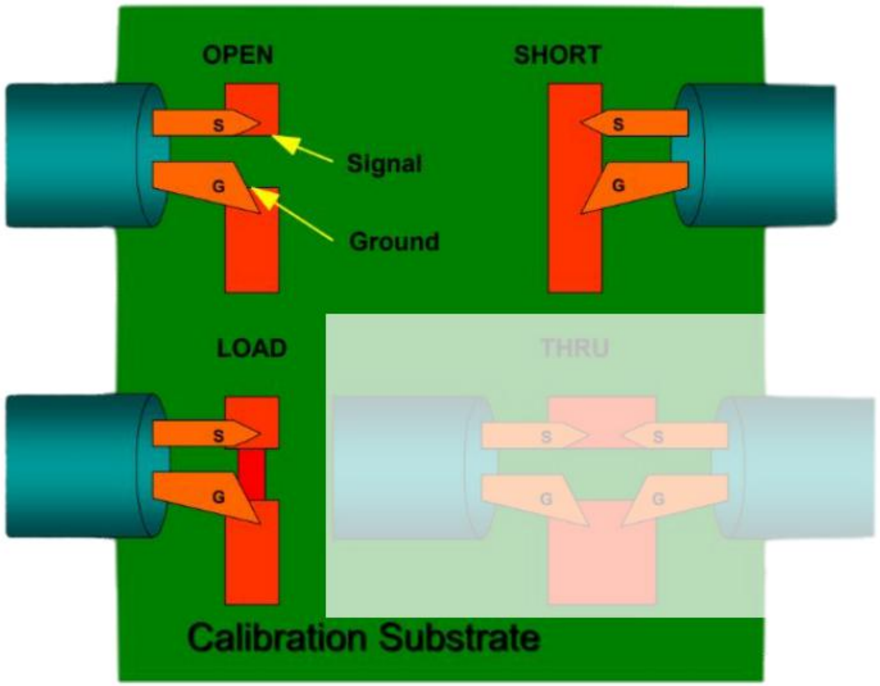




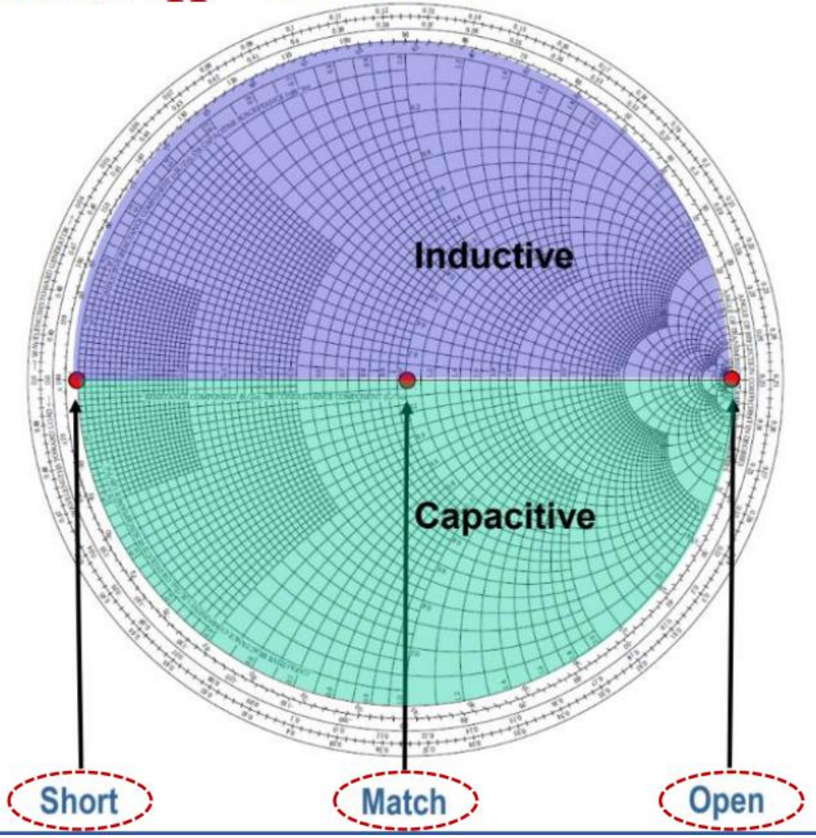


SOL校准方法，以在片测试为例

SOL校准件



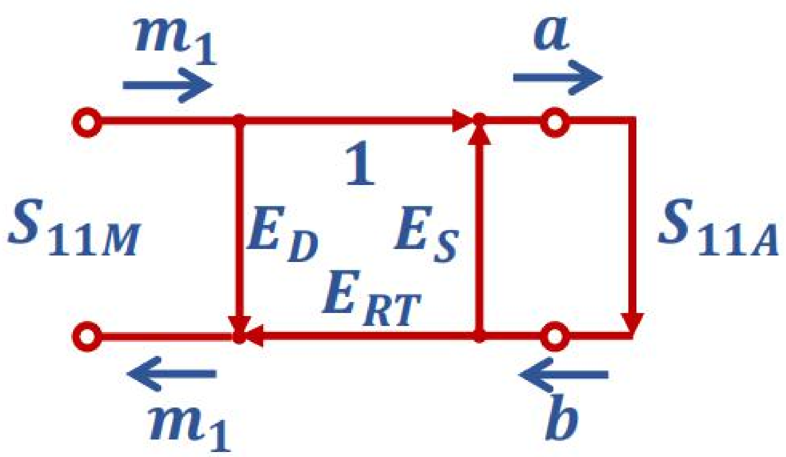
分析阻抗S_{11}：Smith chart



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}

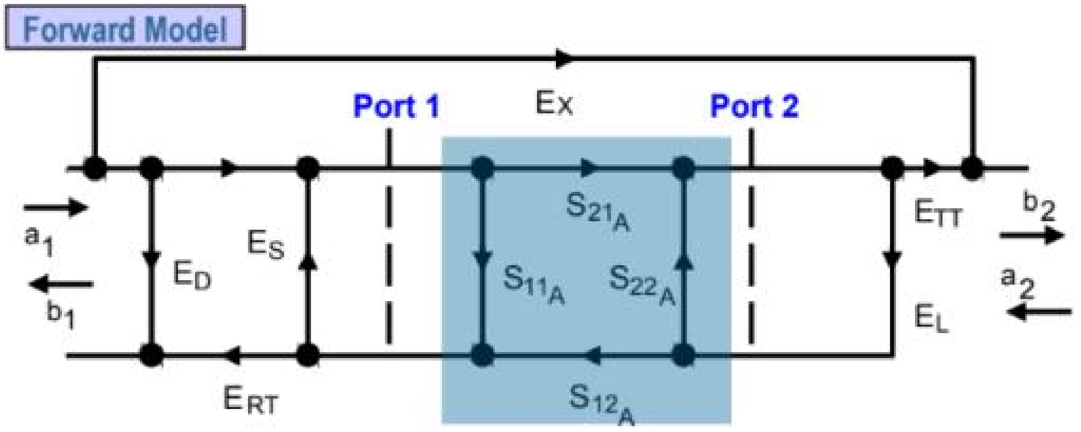
SOLT校准（双端口校准）

Step 1：分别对双端口进行SOL校准；

Step 2：引入thru

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

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

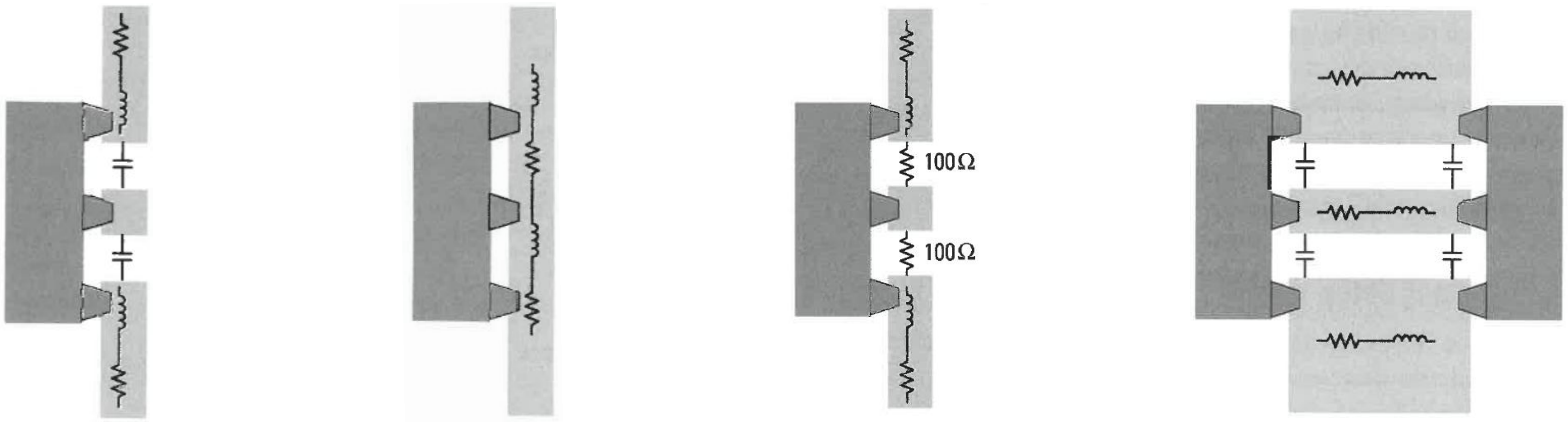


$$\begin{bmatrix} S_{11A} & S_{12A} \\ S_{21A} & S_{22A} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

对reverse model的5个参数同理

校准件中的寄生参数

- Parasitic capacitance and inductance associated with standards may need to be taken into account when performing on-wafer calibration to probe tips.
- Probe manufacturers usually specify calibration coefficients for a specific probe spacing used with a particular impedance standard substrate (ISS).



OPEN SHORT LOAD THRU

$C(f)=C_0+C_1\cdot f+C_2\cdot f^2+C_3\cdot f^3$

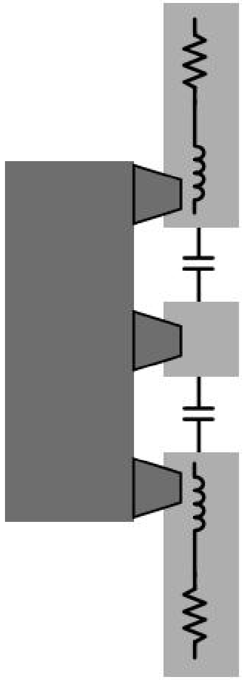
$L(f)=L_0+L_1\cdot f+L_2\cdot f^2+L_3\cdot f^3$

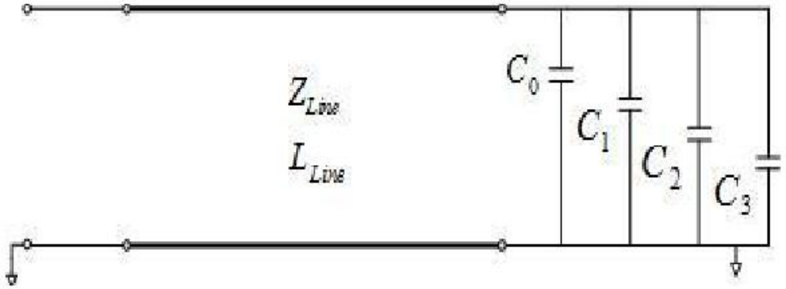
Complex impedance with real part around 50Ω

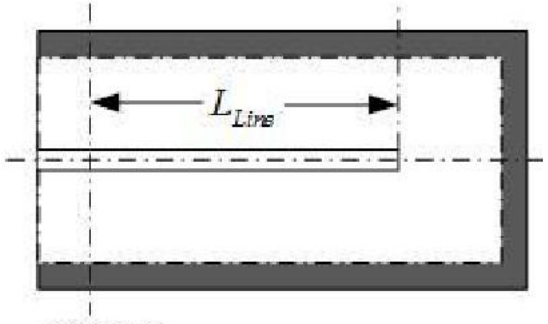
$Delay=l\cdot\sqrt{\varepsilon_r}/c$

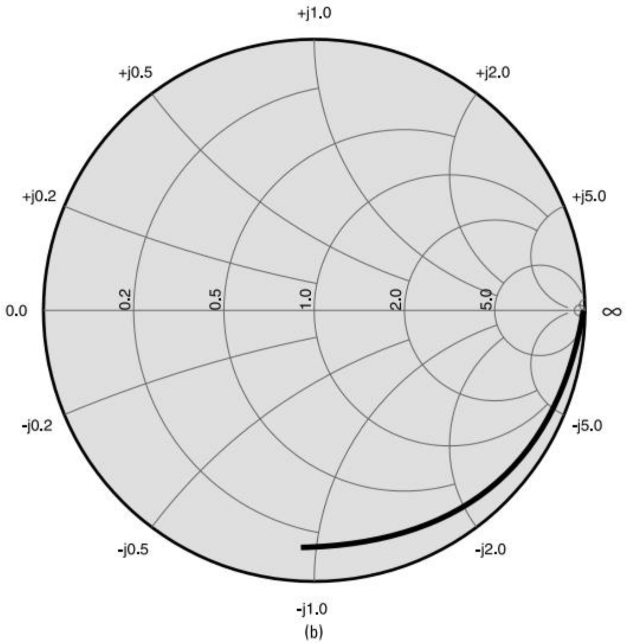
[Lourandakis, 2016]

OPEN的主要特征是其寄生电容C，由信号基板和两个相邻的接地网形成









$$C = C_0 + C_1 f + C_2 f^2 + C_3 f^3$$

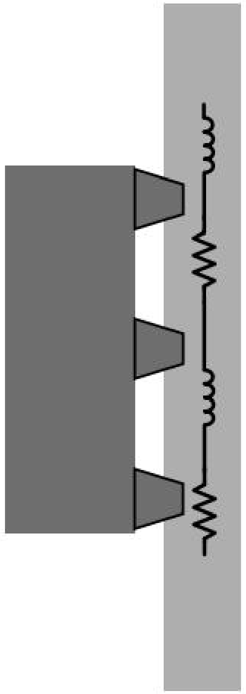
$$Y = j\omega C$$

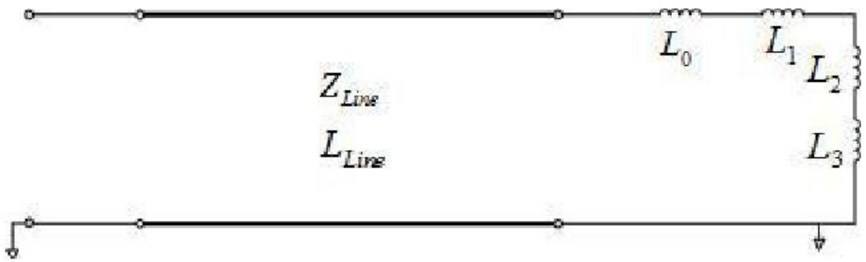
$$T = \frac{1 - Z_r Y}{1 + Z_r Y}$$

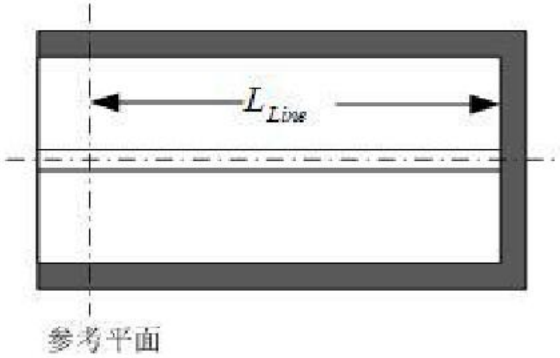
Table 1.6
OPEN Calibration Coefficient for GSG Probe

GSG Probe Pitch (μm)	C_0 (fF) (on substrate)	C_0 (fF) (in air)
100	3.6	−6.5
150	3.7	−6.7
200	3.9	−6.8

SHORT的主要特征是它的寄生电感L，由信号引脚和两个相邻的接地引脚之间的金属带形成



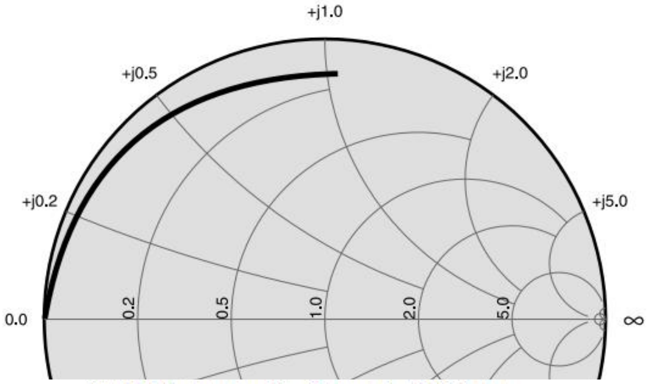




$$L = L_0 + L_1 f + L_2 f^2 + L_3 f^3$$

$$Z = j\omega L$$

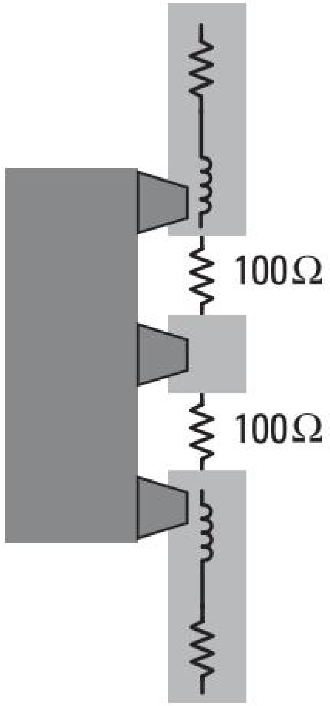
$$T = \frac{Z - Z_r}{Z + Z_r}$$



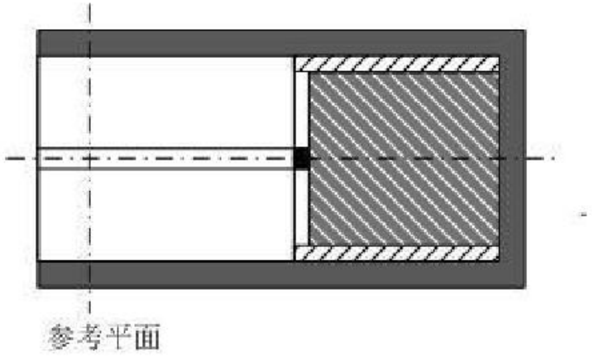
SHORT Calibration Coefficient for GSG Probe

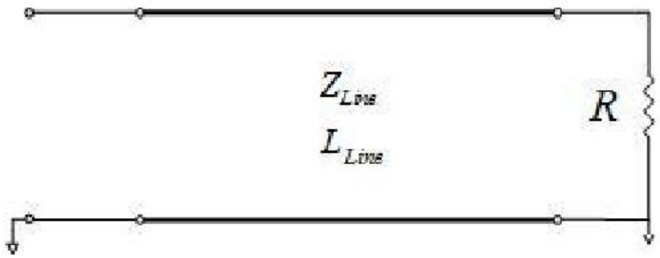
GSG Probe Pitch (μm)	Short Inductance (pH)
100	3.3
150	8.2
200	13.2

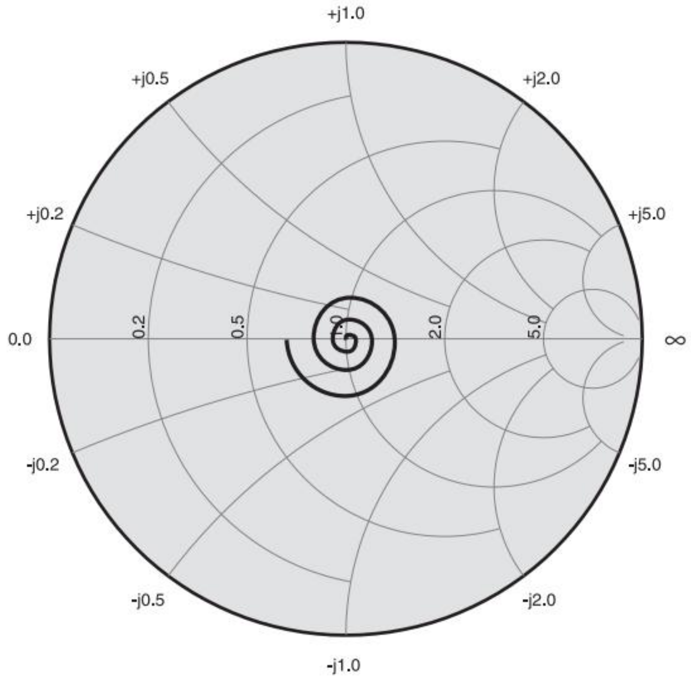
LOAD标准用于设置系统阻抗，通常校准为50Ω



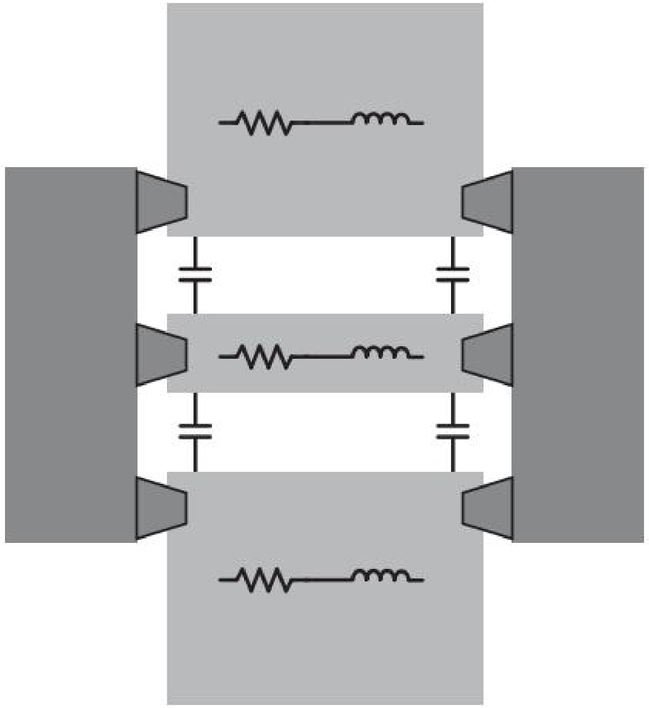
Complex impedance with real part around 50Ω

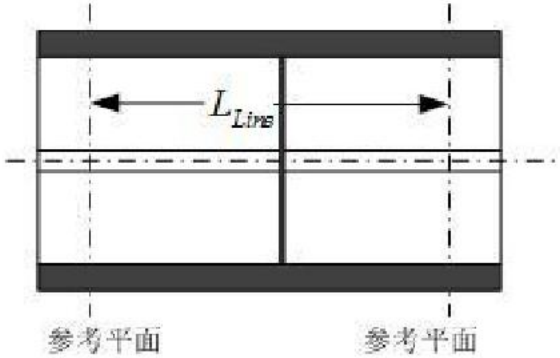


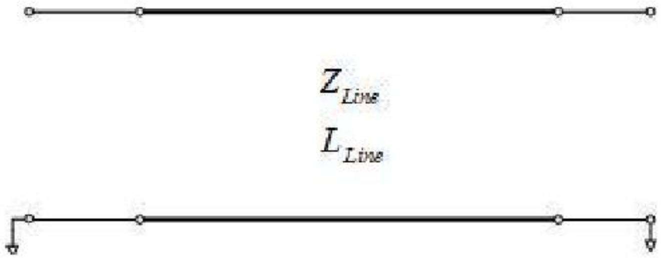




THRU用于在校准过程中设置电参考平面







$$Delay = \frac{l\sqrt{\varepsilon_r}}{c}$$

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	S11, S21, S12, S22； 或者 R, L, C, G; 或者γ, Zc (4个已知量)	Z0=50Ω α=0, τ=0.5pS
Open	S11 (or S22) known	2个已知量	R=inf C=0.3fF
Short	S11 (or S22) known	2个已知量	R=0 L=9pH
Load(Match)	S11 (or S22) known	Z=R+jωL， R和L已知(2个已知量)	R=50 **L=10.6pH**

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.

SOL/SOLT小结

- 1. 以short open load thru 作为校准件（标准）
- 2. 这四个标准同样的重要（想想看为什么？）
- 3. 可以实现非常宽的带宽，但是不适合用于高频校准（100GHz以上）
- 4. 需要对校准件进行精确的定义
- 5. 因此，高频测试需要另外的校准方法。

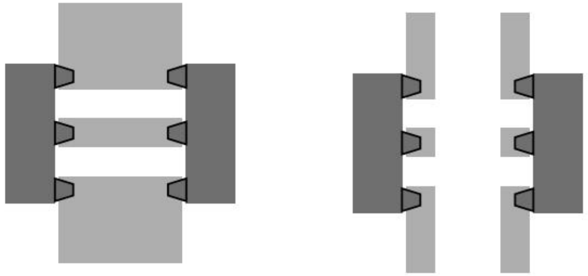
$$S_{11A} = \frac{S_{11M} - E_D}{E_S(S_{11M} - E_D) + E_{RT}}$$

TRL和MultilineTRL校准算法

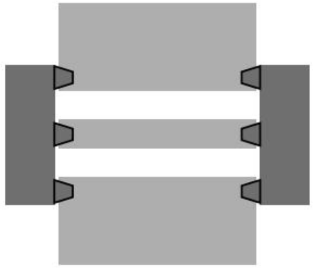
适合于非同轴环境测量，例如 PCB 上表贴器件，波导，夹具，片上测量

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)

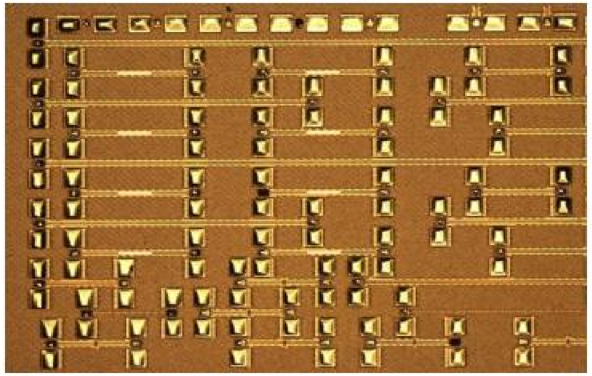


(a) (b)

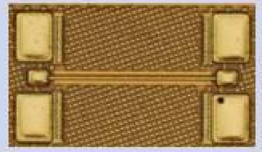
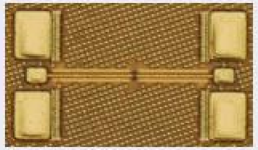
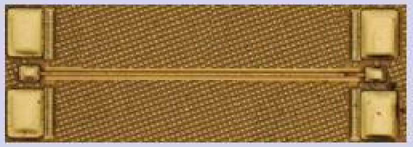


简单的往往是最好的!

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 γ 的值

如何使Line和Thru不同？

无损耗传输线阻抗有λ/4变化性和λ/2重复性

¼ 波长传输线的特点：*90度相移，可以将开路/短路变短路/开路*

$$Z_{in}=Z_0\frac{Z_L+Z_0\text{th}(\gamma l)}{Z_0+Z_L\text{th}(\gamma l)} \qquad \Gamma_{in}=\Gamma_L e^{-2\gamma l}$$

$$Z_{in}=Z_0\frac{Z_L+jZ_0\text{tg}(\beta l)}{Z_0+jZ_L\text{tg}(\beta l)}\text{（无损耗）} \qquad \Gamma_{in}=\Gamma_L\ e^{-2j\beta l} \qquad \boldsymbol{\beta l}=\frac{\mathbf{2\pi}}{\boldsymbol{\lambda}}\boldsymbol{l}=\textbf{电长度}$$

转半圈　　90度　　*λ/4*

传输线相位变化

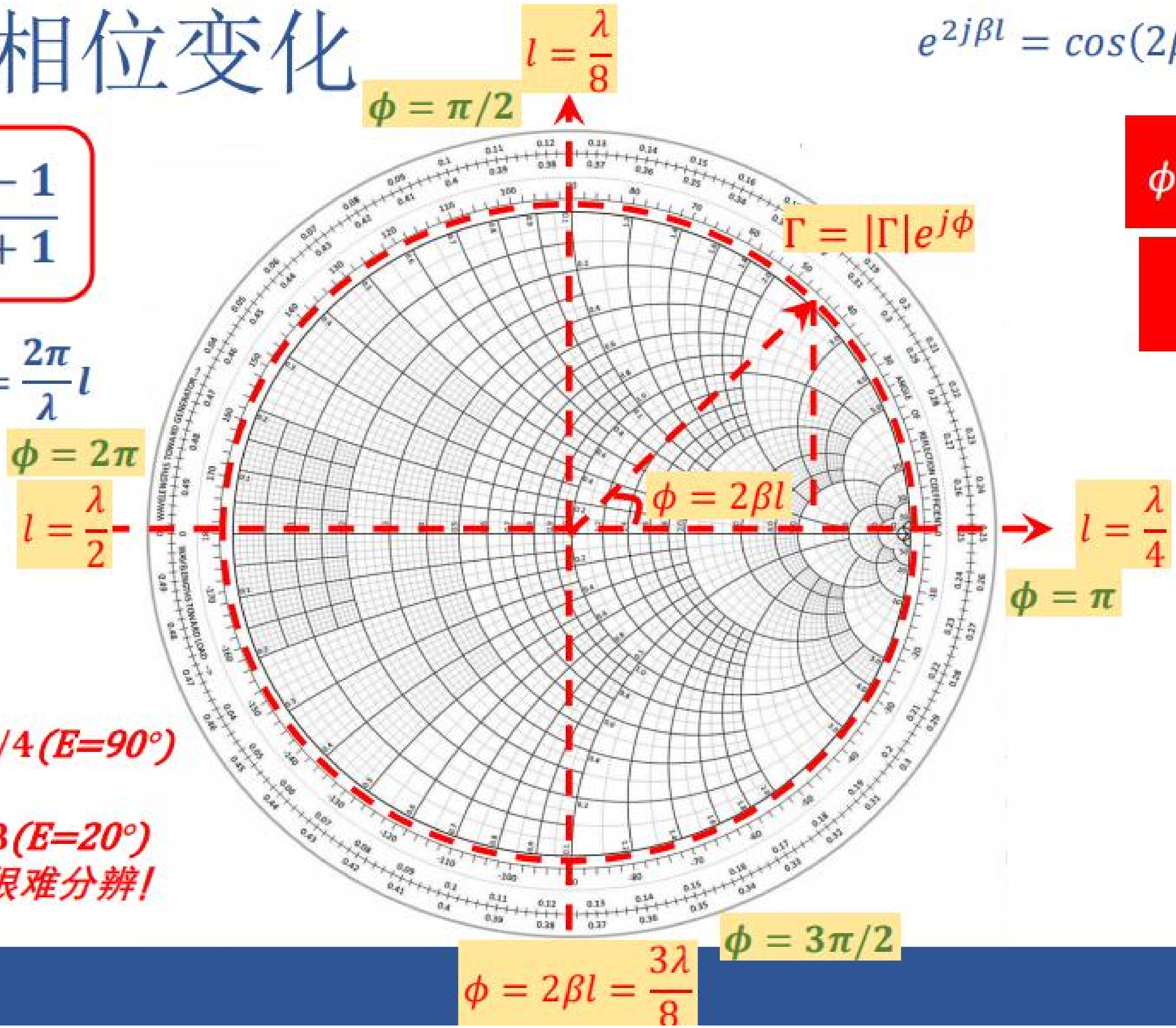
$$e^{2j\beta l} = cos(2\beta l) + jsin(2\beta l)$$

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

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

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

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

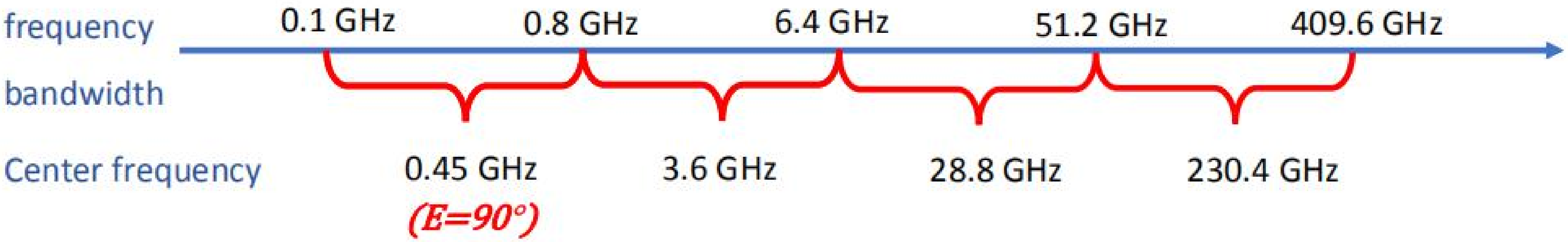


两条输线相差 λ/4 (E=90°) 时相位差最大！

相位差在<λ/18 (E=20°) 和> 4λ/9 (E=160°)很难分辨！

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？

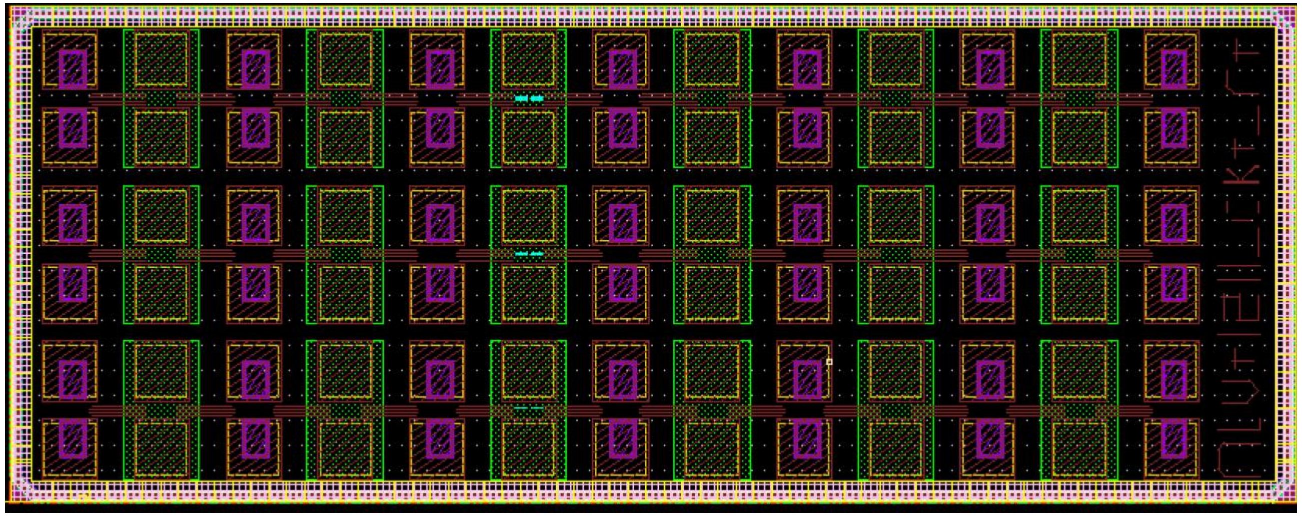
Step 3：确定Line的长度　中心频率的1/4波长，easy！

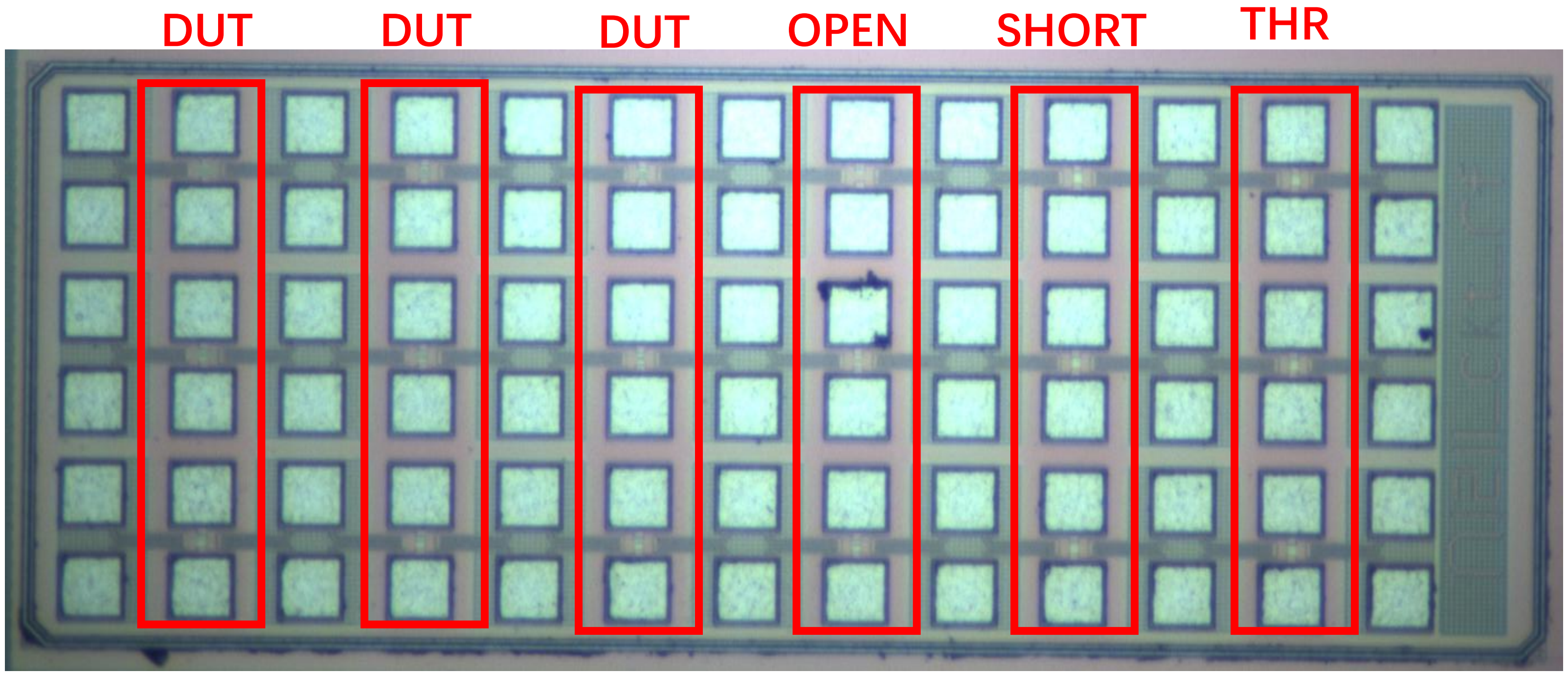
TRL 小结

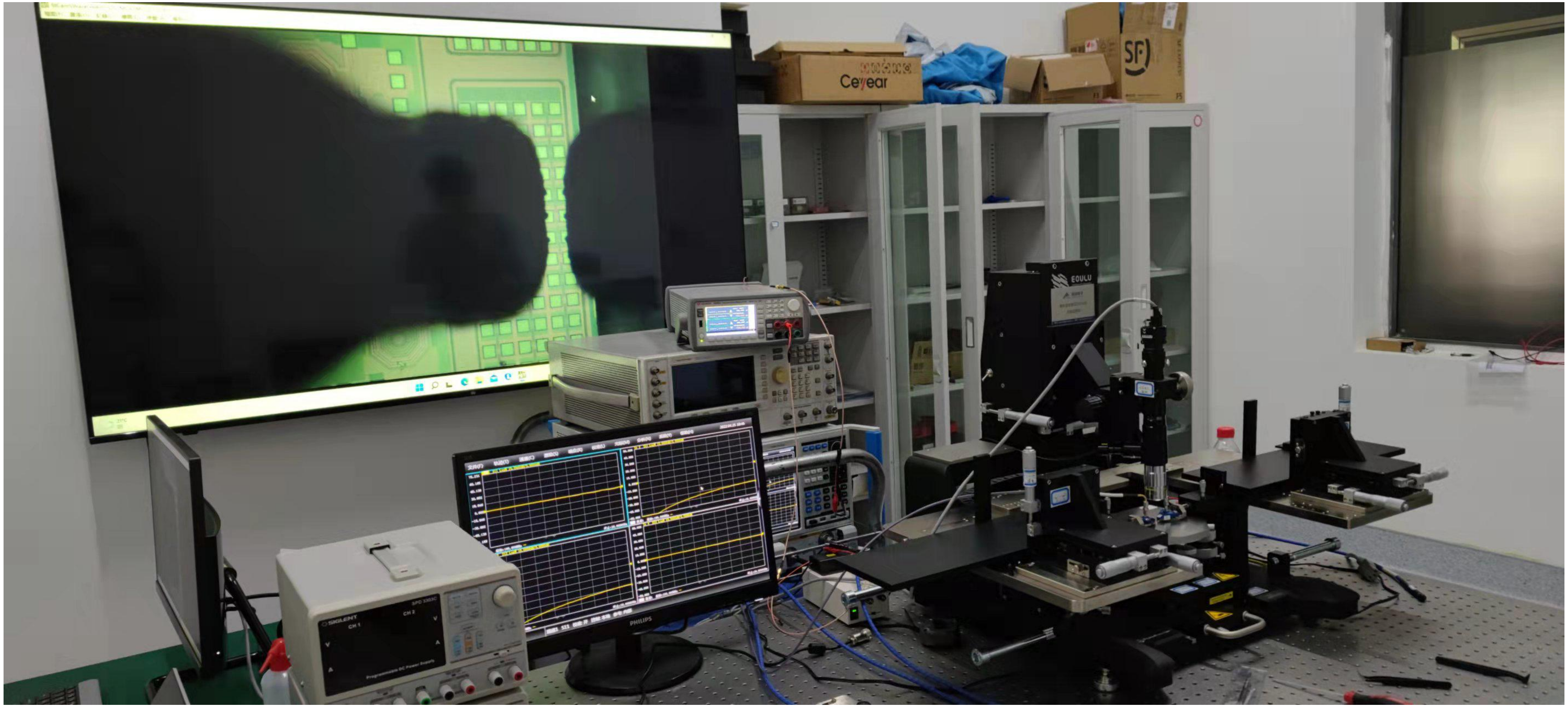
- 1. Line Thru Reflect（open或short） 作为校准件（标准）
- 2. 最重要的标准是Line
- 3. 不需要定义校准件（无需知道校准件的寄生参数）
- 4. 带宽最多8倍
- 5. 适合用于灵活的测量

案例1：MOSFET 测试

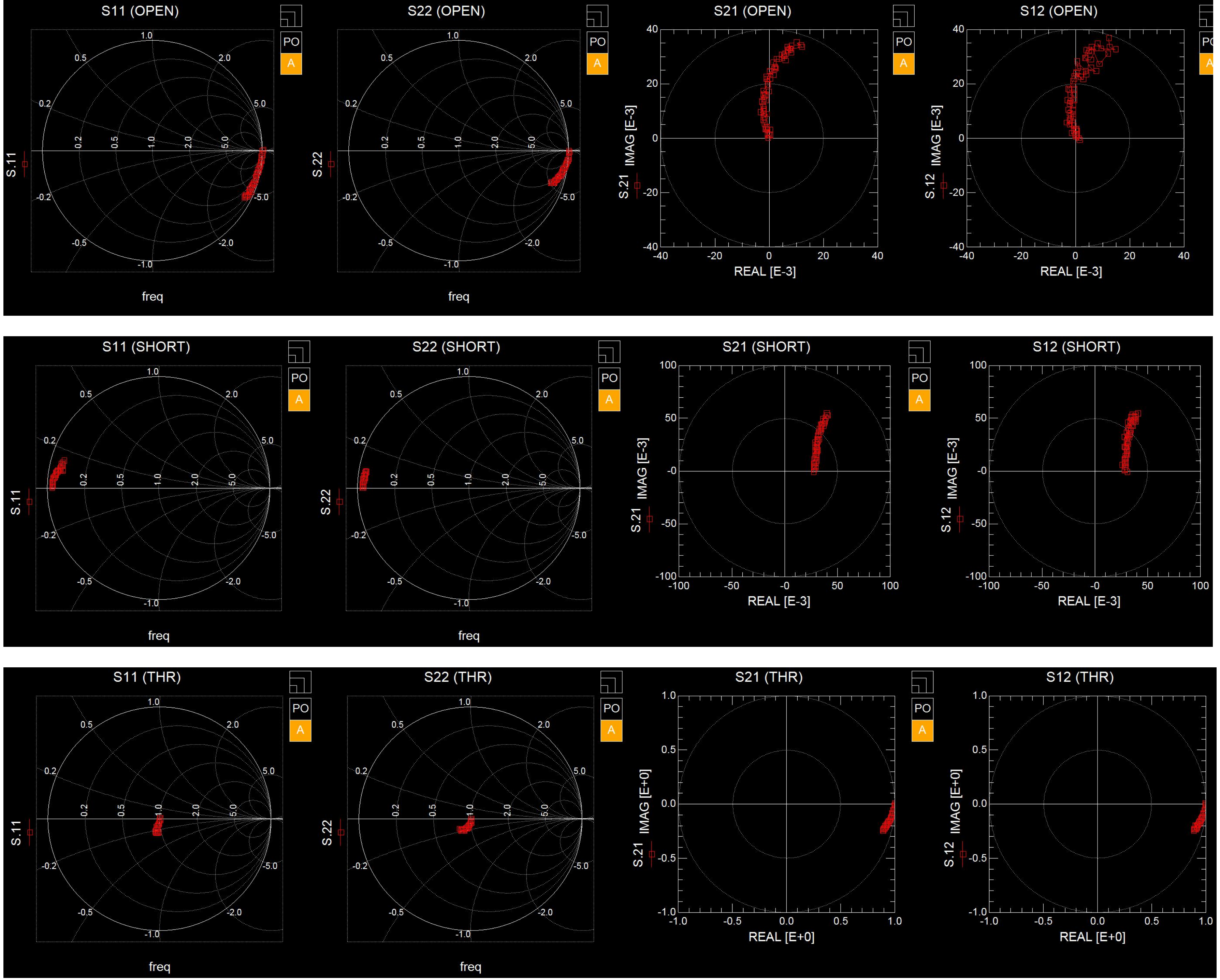
1. 采用了自定义的TRL校准件
2. 采用不同的偏压，测试了FET去嵌入前后的S参数
3. 精确获取了MOSFET的模型




DUT
DUT
DUT
OPEN
SHORT
THR

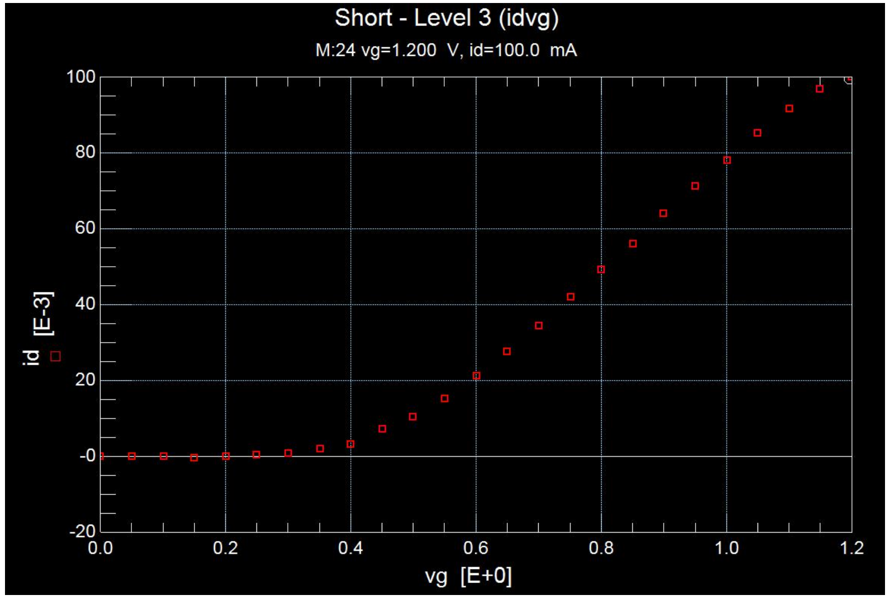

Ceyear
EOULU
PHILIPS
SIGLENT

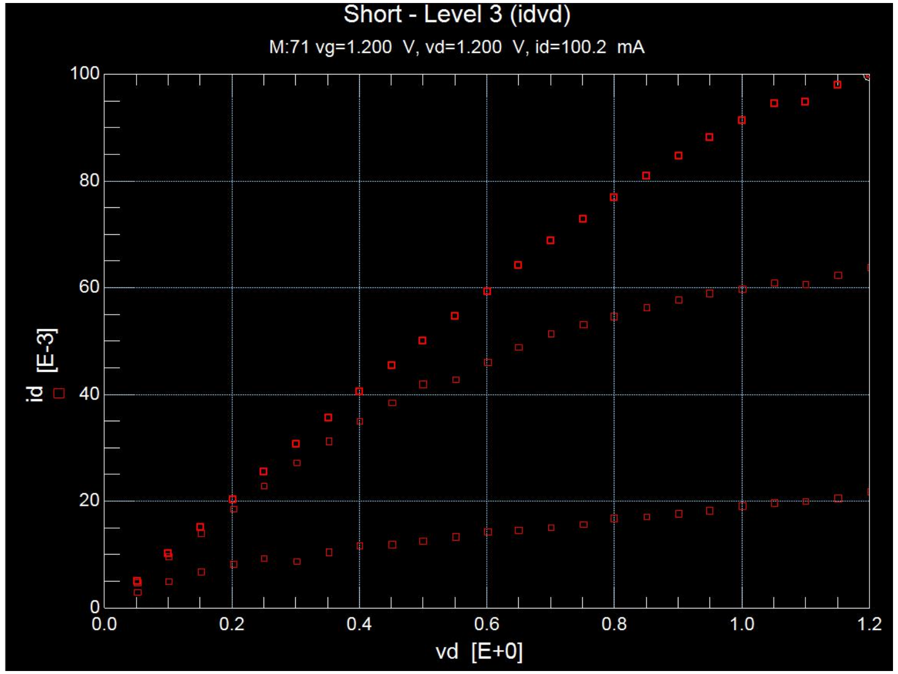
- Cal_5u_300K
  - open
  - short
  - through
- n12rf_5u6060n__300K
  - idvg
  - idvd
  - sdut_00
  - sdut_06
  - sdut_12
  - sdut_vg
  - sdut_vd
  - sdut_10



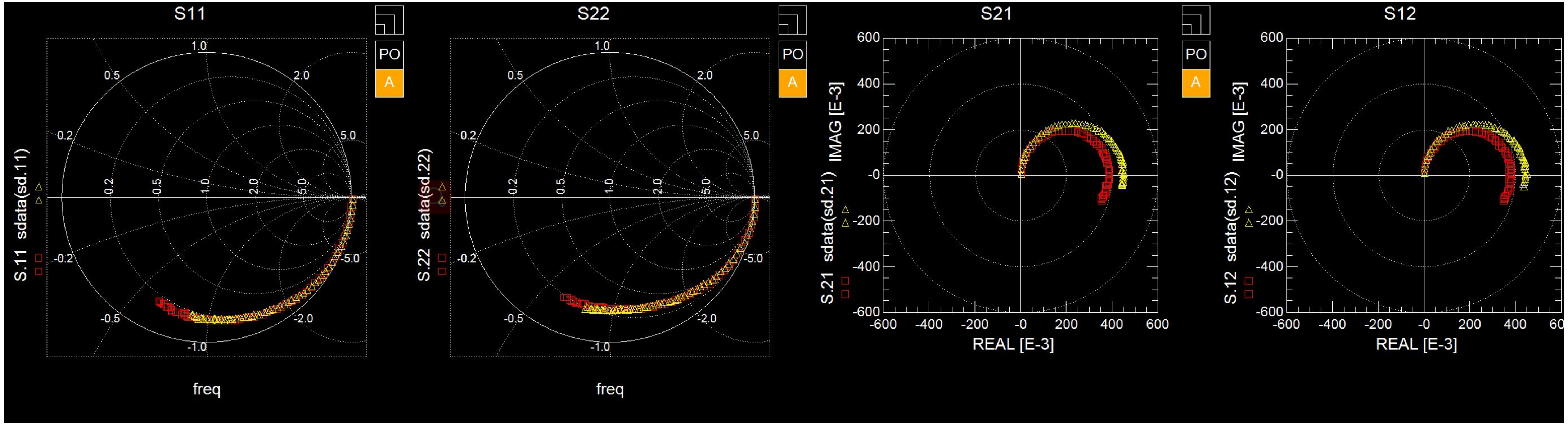
1. IV测试确保管子正常工作

- Cal_5u_300K
  - open
  - short
  - through
- n12rf_5u6060n__300K
  - idvg
  - idvd
  - sdut_00
  - sdut_06
  - sdut_12
  - sdut_vg
  - sdut_vd
  - sdut_10

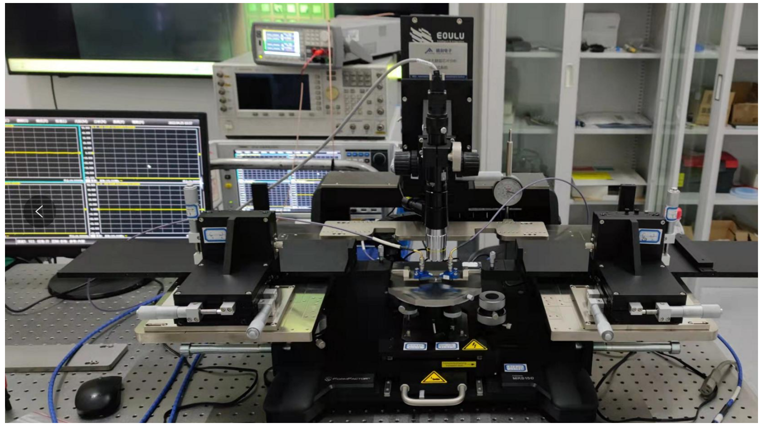




2. S参数测试及去嵌入

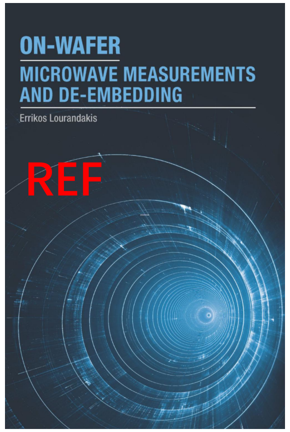


红色为测试原始数据，黄色为去嵌入后数据



```
Ytotal    = TwoPort(S,         "S", "Y")
Yopen     = TwoPort(Sopen,     "S", "Y")
Yshort    = TwoPort(Sshort,    "S", "Y")
Ztotal_2  = TwoPort(Ytotal - Yopen, "Y", "Z")
Zshort_2  = TwoPort(Yshort - Yopen, "Y", "Z")
Sdut      = TwoPort(Ztotal_2 - Zshort_2, "Z", "S")
```

去嵌算法



本章思考题

- 1. 推导SOLT算法的相关公式，并解释寄生参数的重要性和对测试的影响（2-3人）
- 2. 推导TRL 算法的相关公式，并解释为什么其最重要的标准是Line校准件，且解释为什么该校准方法不关心校准件的寄生参数（2-3人）

3. 调研利用探针台测试四端口无源器件的方法，并描述校准的过程 （3-4人）

4. 调研利用探针台测试混频器（三端口器件）的方法，并描述校准的过程（3-4人）