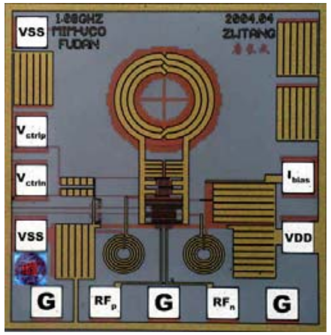

CMOS射频集成电路设计

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复旦大学 专用集成电路与系统国家重点实验室

片上螺旋电感

- 简介
- 射频集成电路中的电感
- 片上螺旋电感
- 平面螺旋电感的分析和建模
- 等效电容的计算
- 提高品质因数的几种方法
- 片上电感的在片测试
- 中心抽头差分电感的等效模型和参数提取

简介

- 射频集成电路的市场潜力
  - ❑无线收发机：**WLAN, Bluetooth, WCDMA, TD-SCDMA**
  - ❑宽带调谐器：**Mobile Tuner, DVB-T TV Tuner**
- **CMOS**技术的发展
  - ❑工作频率**<10GHz**，截止频率**30-50GHz**
  - ❑比**GaAs, SiGe, Bipolar**工艺便宜
  - ❑高集成，高性能
    - ❖数字和模拟
    - ❖有源和无源器件：**MOS**, 二极管，电阻，电容，电感
- 设计电感能否像**MOS**管一样方便？
  - ❑建模是难点
  - ❑品质因数**Q**的优化和自激振荡频率f_{RS}的优化

片上电感的三种类型

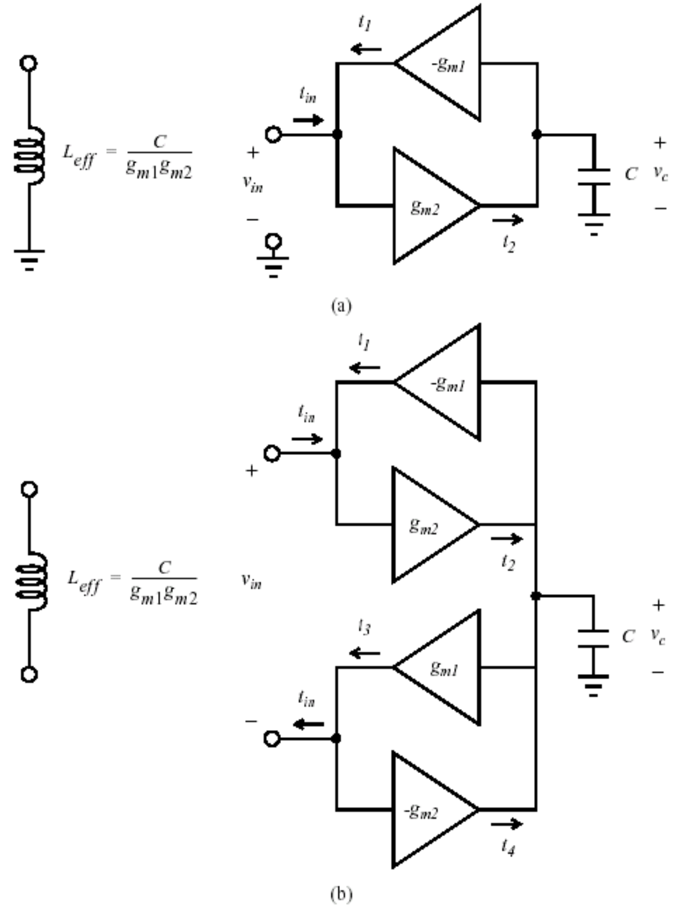


图1 有源电感

(a) 单端结构，(b) 双端结构

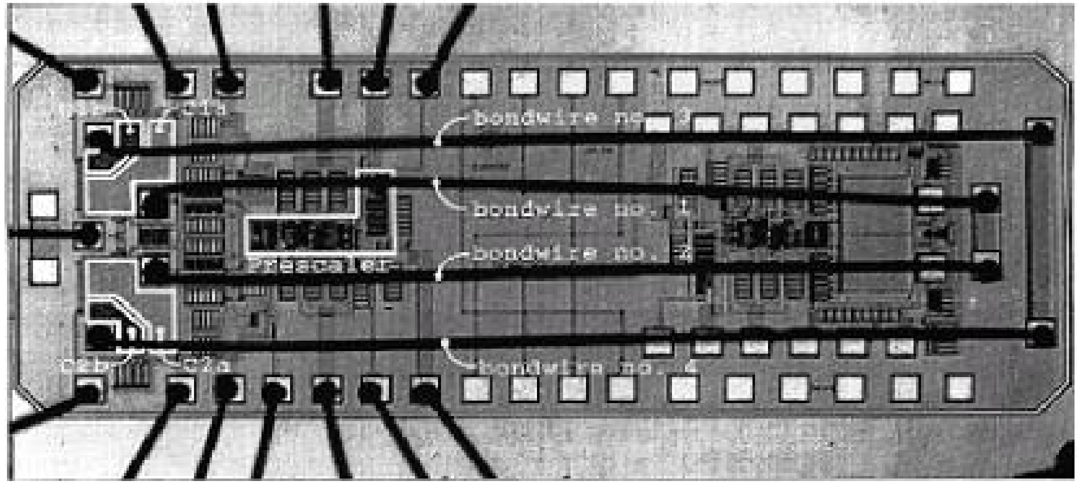


图2 键合线电感

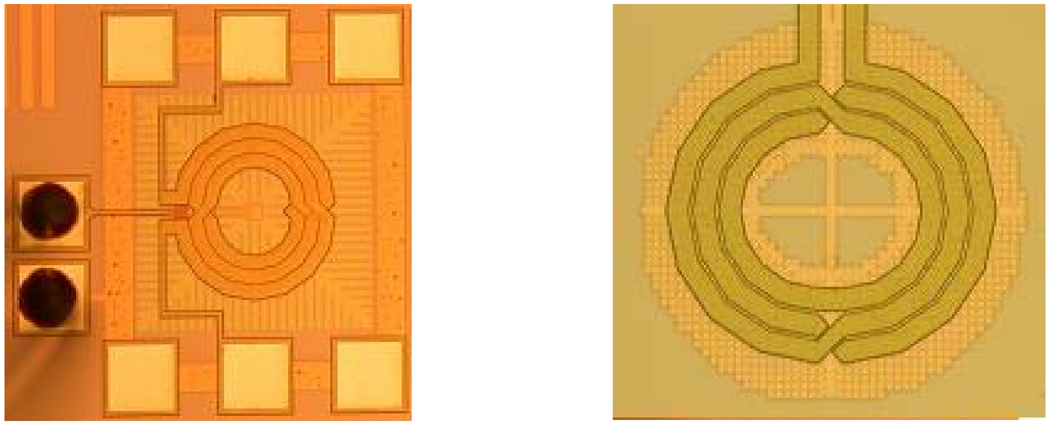


图3 片上螺旋电感

射频集成电路中的电感(I)

- 射频集成电路
  - ❑低噪声放大器，混频器，压控振荡器，功率放大器，高频带通滤波器和阻抗匹配网络

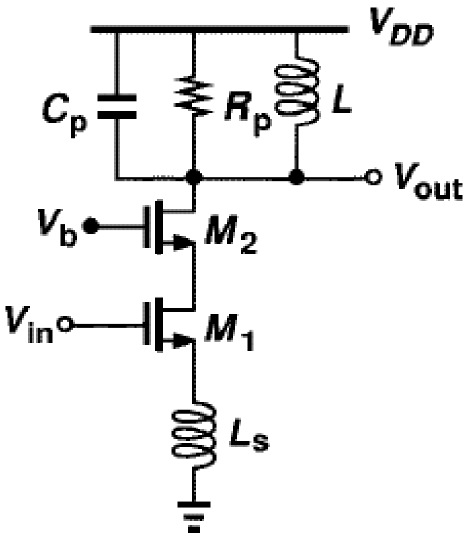


图1 低噪声放大器

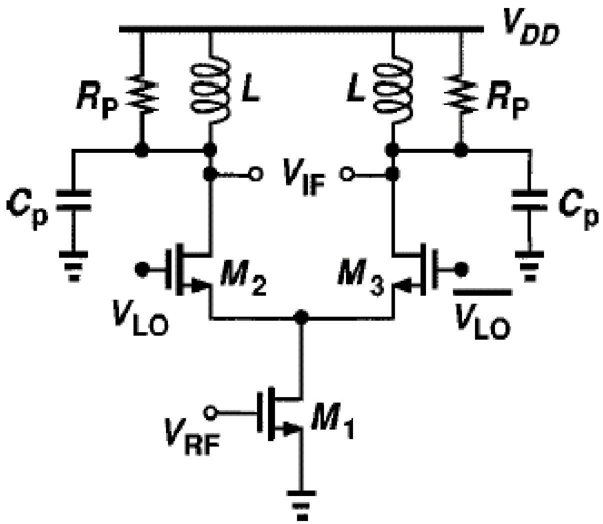
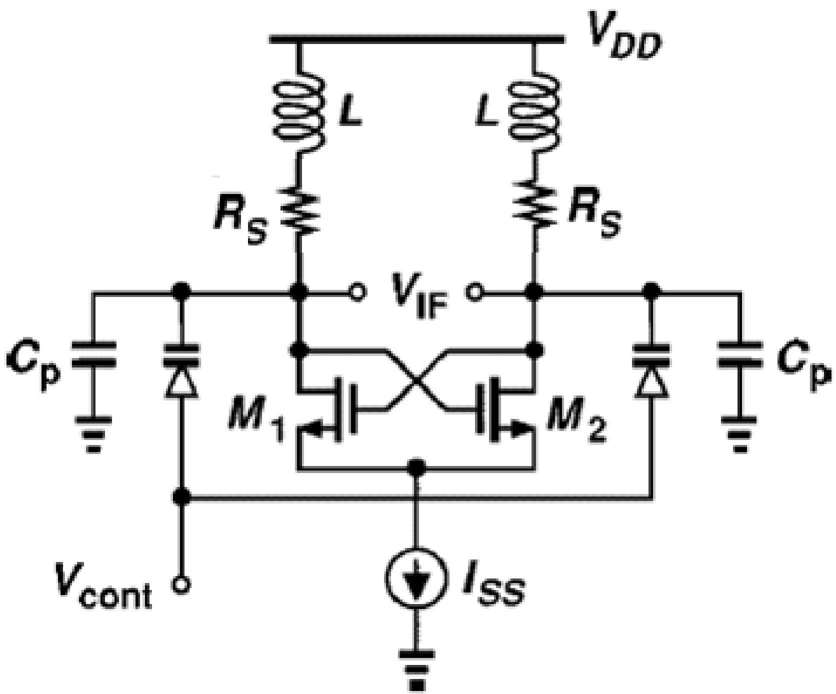


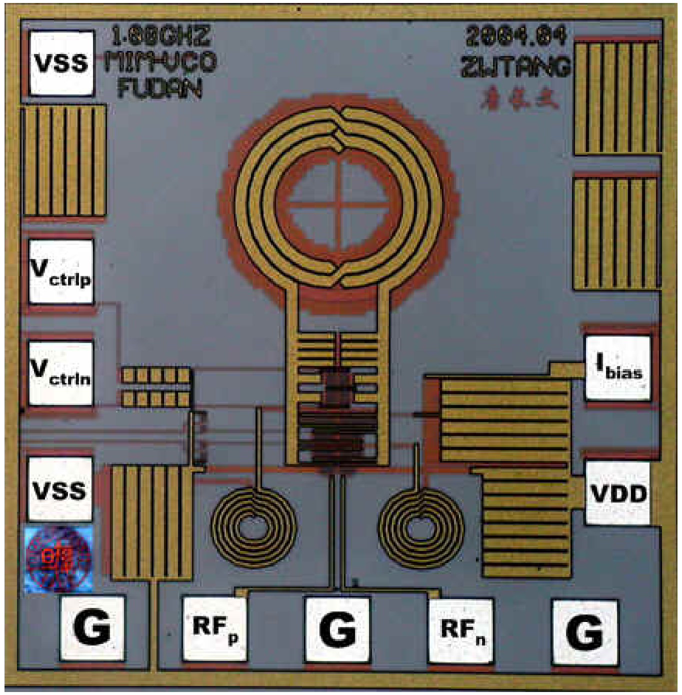
图2 频混频器

为了提高增益(转换增益)，增大片上电感的等效并联电阻。



压控振荡器电路与版图照片

- 为了提高品质因数，降低片上电感的串联电阻。
- 为了提高压控振荡器的调谐范围，减小并联电容。



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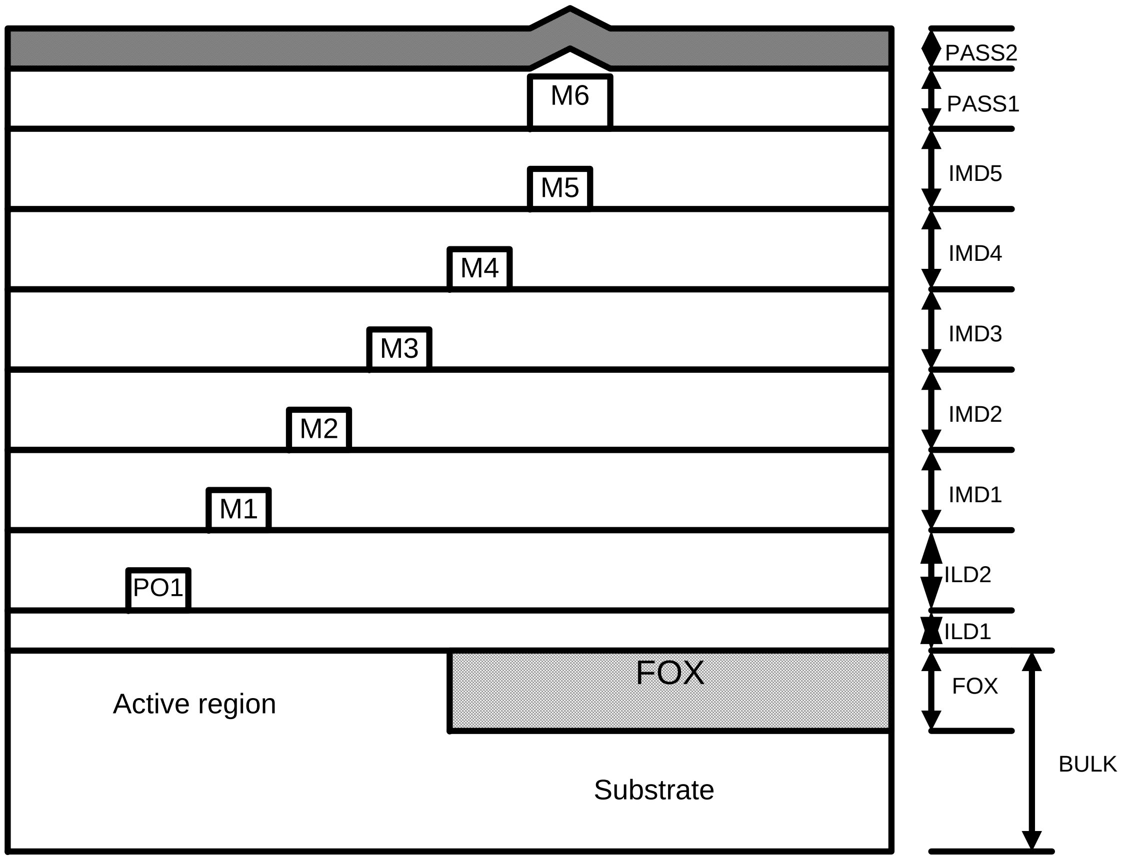
射频集成电路中的电感(II)

- 片上电感的功能和作用

电路	功能	作用
低噪声放大器	输入阻抗匹配 源极退化 谐振负载	同时满足功率和噪声的匹配 提高线性度 线性度最佳偏置，滤波，消除寄生电容的影响
混频器	源极退化	增加线性度，减小噪声
振荡器	谐振	确定振荡频率，高品质因数电路 降低功耗，减小相位噪声
功率放大器	功率匹配 谐振负载	增大电压摆幅，提高功率效率

片上螺旋电感

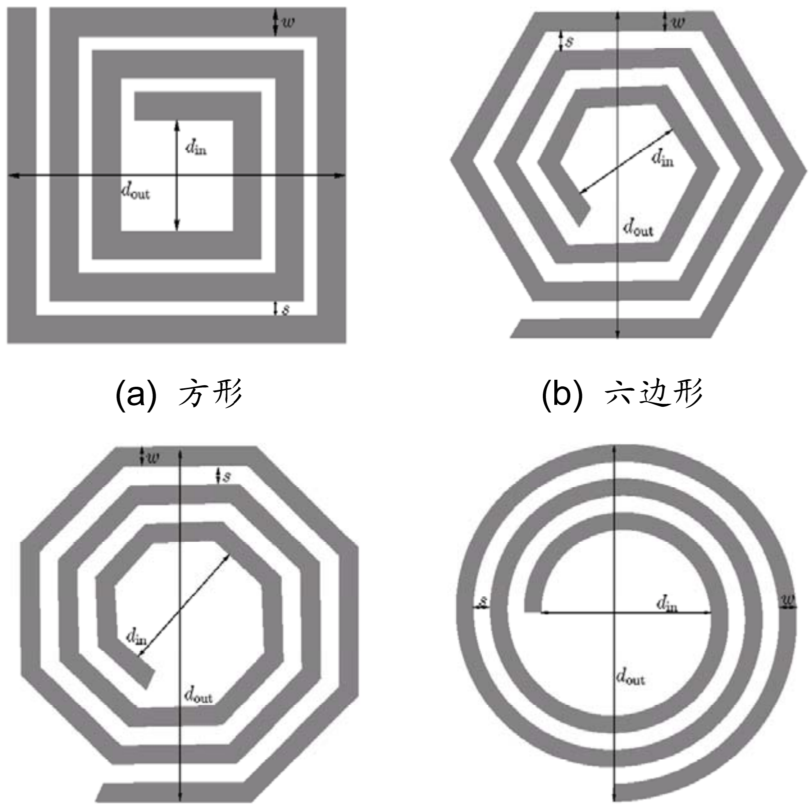
- **CMOS工艺互连线**



CMOS工艺互连线剖面图

平面螺旋电感(I)

- 横向参数
  - 圈数，**n**
  - 金属宽度，**w**
  - 金属间距，**s**
  - 外直径，$\mathbf{d_{out}}$
    内直径，$\mathbf{d_{in}}$
    填充率，
    $\rho = (d_{out} - d_{in})/(d_{out} + d_{in})$
  - 边数，**N**

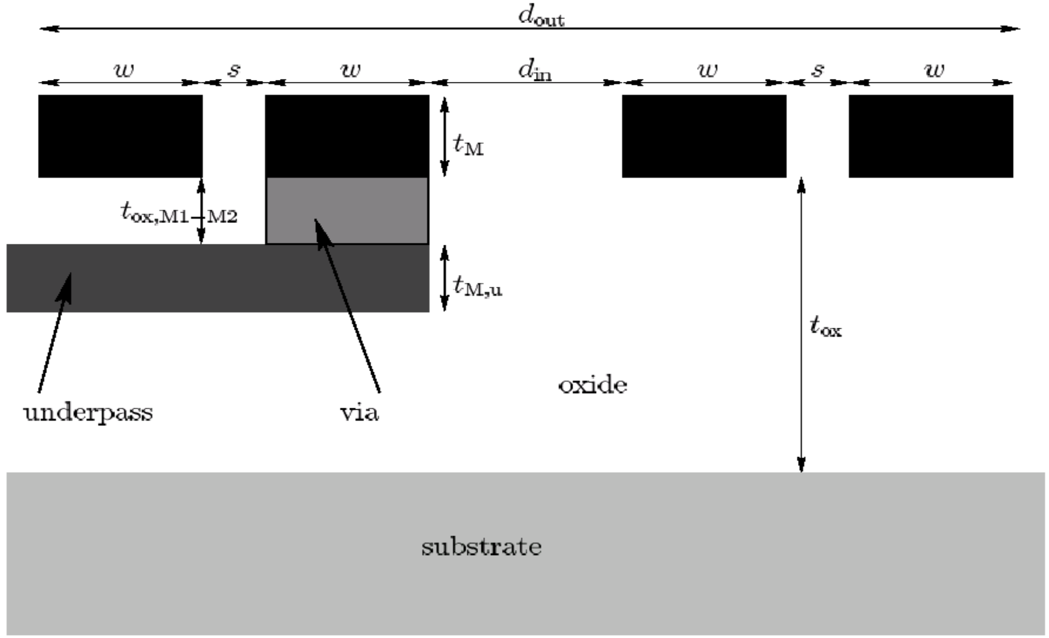


(a) 方形　(b) 六边形　(c) 八边形　(d) 圆形

平面螺旋电感

平面螺旋电感(II)

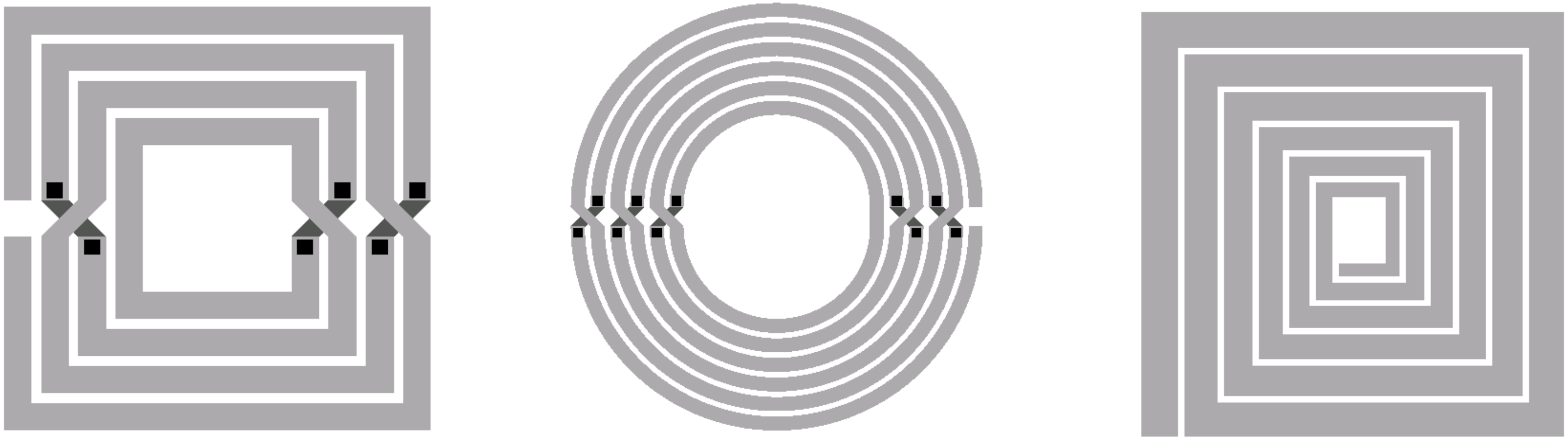
- 垂直参数
  - 金属厚度，t_M, $t_{M,u}$
  - 氧化层厚度，t_{ox}
  - 金属间氧化层厚度，tox,M1-M2
  - 衬底厚度，t_{sub}



方形电感的垂直参数

其他平面螺旋电感

- 对称螺旋电感
- 非等宽螺旋电感



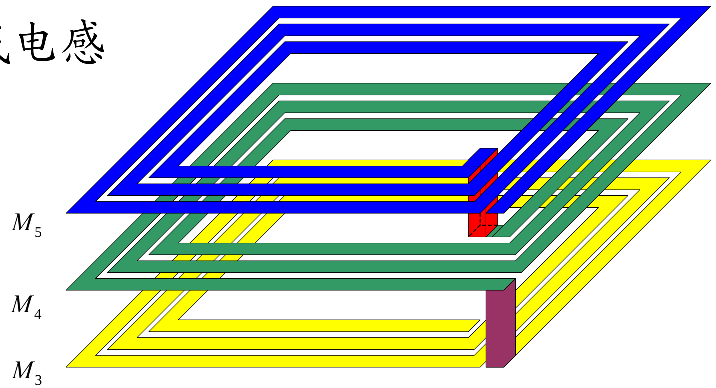
(a) 对称方形电感　(b) 对称圆形电感　(c) 非等宽方形电感

其他平面螺旋电感

多层叠成螺旋电感

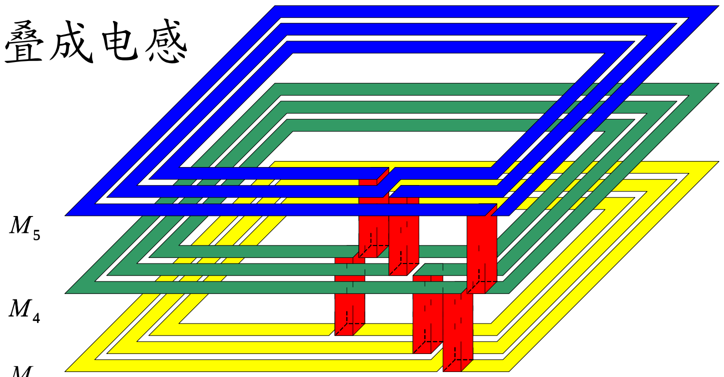
- 叠成电感
- 3D叠成电感

叠成电感



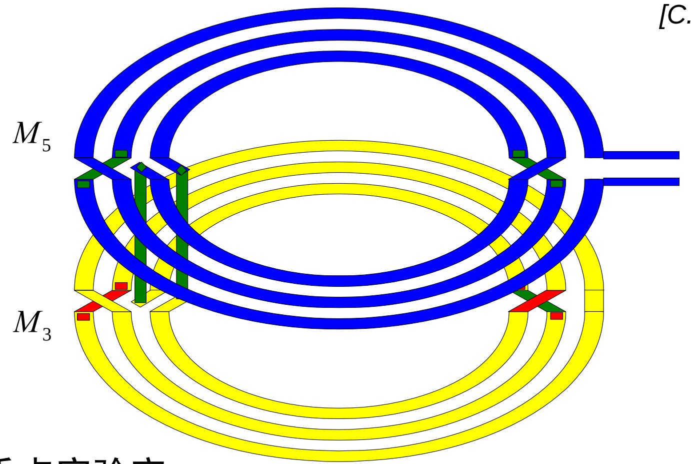
[A. Zolfaghari, B. Razavi, JSSC, April, 2001]

3D 叠成电感



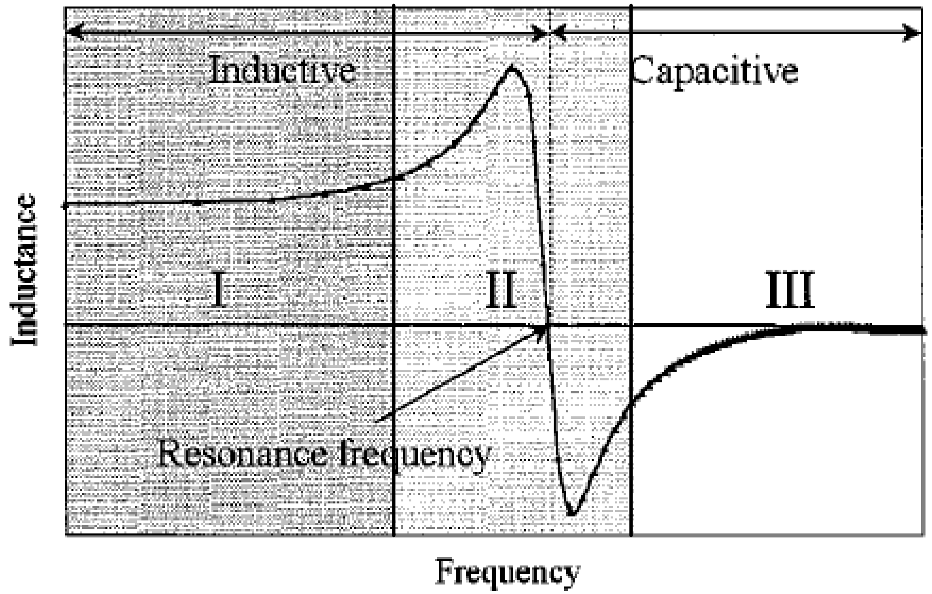
[C.C Tang, S.I. Liu, JSSC, April, 2002]

差分叠成电感



片上螺旋电感的分析与建模

- 电感的仿真与建模
  - ❑电磁场仿真工具
  - ❑分段电路模型
  - ❑精简集总电路模型



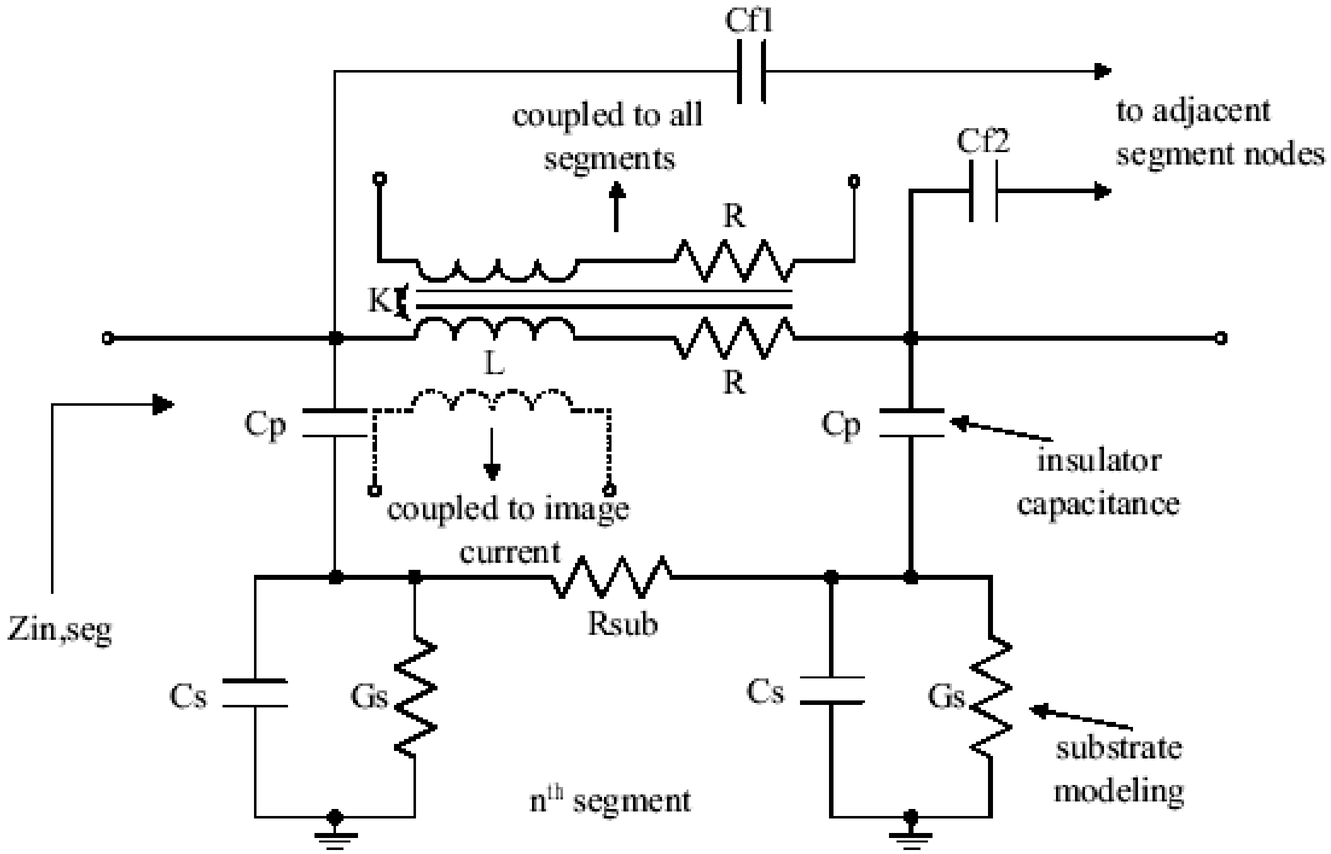
片上电感的典型频响特性

(1)电磁场仿真工具

- Maxwell方程求解器
  - **Ansoft, EM-Sonnet, Momentum, Microwave Office**
- 优点
  - 高精度，可用于任何结构分布系统的仿真
- 缺点
  - 速度非常慢
  - 需要大量内存进行计算
  - 软件非常昂贵
  - 对于**SPICE**仿真来说，模型非常复杂

(2)分段电路模型(I)

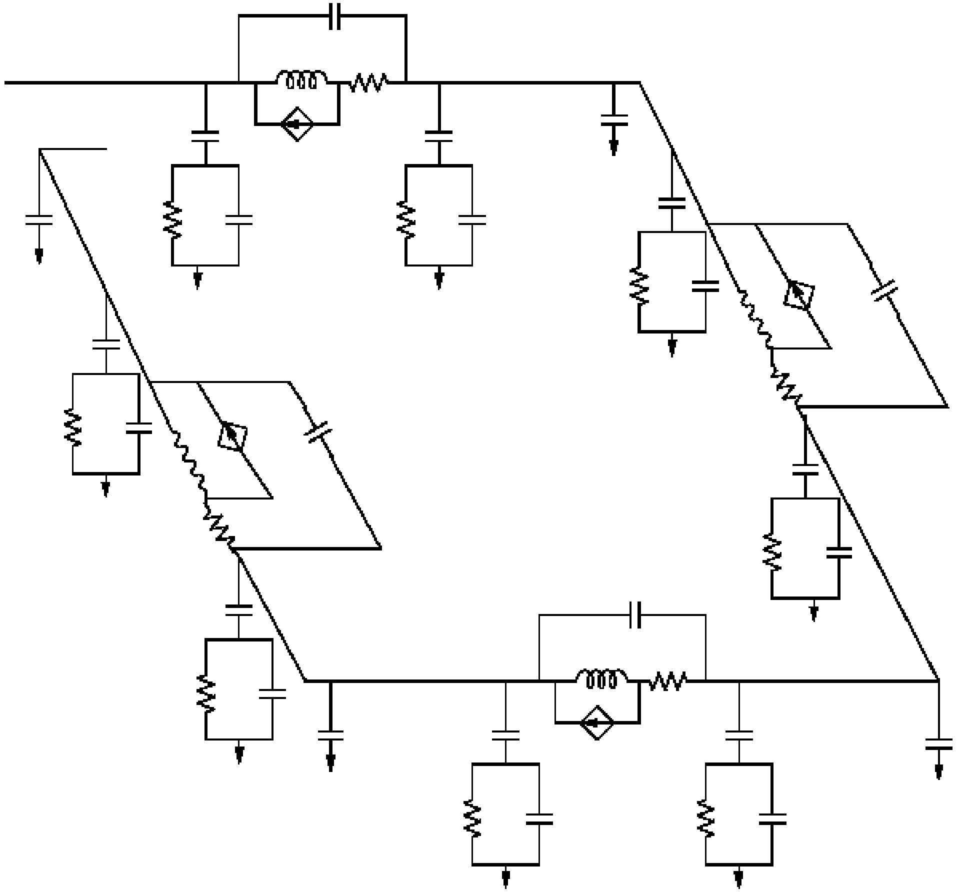
- 对于片上电感的每一条金属建立分段π模型



片上电感的每一段金属的两端等效模型

分段电路模型(II)

- 单圈分段模型



单圈分段等效模型

分段电路模型(III)

- 耦合微带线模型

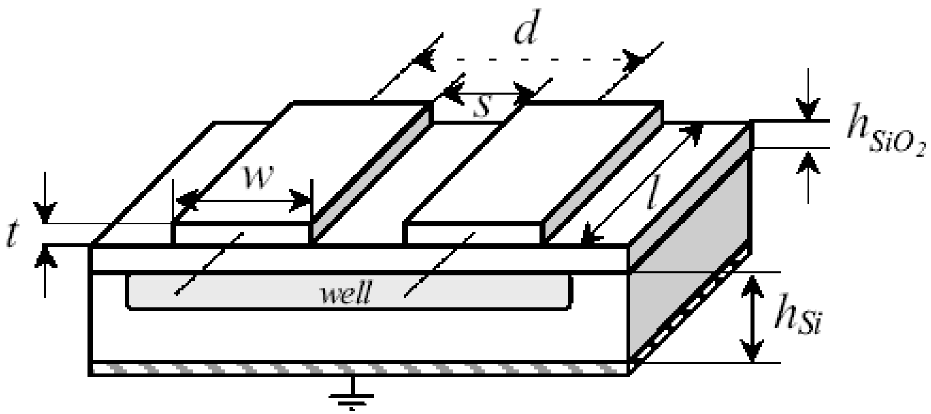


图1 平行微带线的耦合

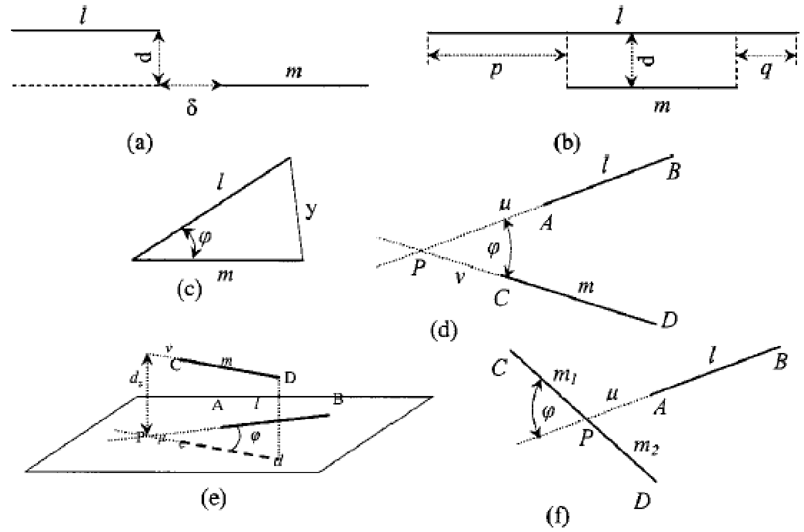


图2 两根金属间的几种耦合方式

分段电路模型(IV)

- π 模型方程

	Equation
$L = 2l\{ln[2l/(w+t)] + 0.50049 + (w+t)/3l\}$	(1)
$R = R_{sh} l / w$	(2)
$C_p = \varepsilon_0 \varepsilon_r w / h$	(3)
$M = 2lU$	(4)
$K_m = M_{1,2} \big/ \sqrt{L_1 L_2}$	(5)
$2M = (M_{l+m\pm\delta} + M_{\delta}) - (M_{l\pm\delta} + M_{m\pm\delta})$	(6)
$2M = (M_{m+p} + M_{m+q}) - (M_p + M_q)$	(7)
$M_{lm} = 2\cos\phi \left[l\tanh^{-1}\left(\frac{m}{l+y}\right) + m\tanh^{-1}\left(\frac{l}{m+y}\right) \right]$	(8)
$M_{lm} = 2\cos\phi \left[(M_{\mu+l,v+m} + M_{\mu v}) - (M_{\mu+l,v} + M_{v+m,\mu}) - \Omega d_z / \sin\phi \right]$	(9)
$\Omega = \frac{\pi}{2} + \tan^{-1}\left[\frac{d_z^2 \cos\phi + lm\sin^2\phi}{d_z R_1 \sin\phi}\right] - \tan^{-1}\left(\frac{d_z\cos\phi}{l\sin\phi}\right) - \tan^{-1}\left(\frac{d_z\cos\phi}{m\sin\phi}\right)$	(10)
$R_{sub} = \rho_{Si} l / (w h_{Si})$	(11)
$C_s = \frac{(w+\Delta w')}{h}\varepsilon_0 \varepsilon_{r\_Si}$, $\Delta w' = \left(1 + \frac{1}{\varepsilon_{r\_Si}}\right)\frac{\Delta w}{2}$, $\Delta w = \frac{t}{\pi} ln\left[4e \Big/ \sqrt{\left(\frac{t}{h}\right)^2 + \left(\frac{1/\pi}{w/t + 1.1}\right)^2}\right]$	(12)
$G_s = \hat{\sigma}\frac{w}{\hat{h}}$, $\hat{\sigma} = \sigma\left(\frac{1}{2} + \frac{1}{2\sqrt{1+10h/w}}\right)$, $\hat{h} = \frac{w}{2\pi} log\left(\frac{8h}{w} + \frac{4w}{h}\right)$	(13)

分段电路模型(V)

- 优点
  - 与电磁场仿真工具相比，非常简单
  - 易于与SPICE软件进行集成
- 缺点
  - SPICE网表比较复杂、繁琐
  - 模型中器件数目太多，降低了SPICE仿真的速度

(3)精简集总电路模型(I)

- 简单，模型中的电阻和电容有明确物理意义
  - ❑ 串联电阻R_S

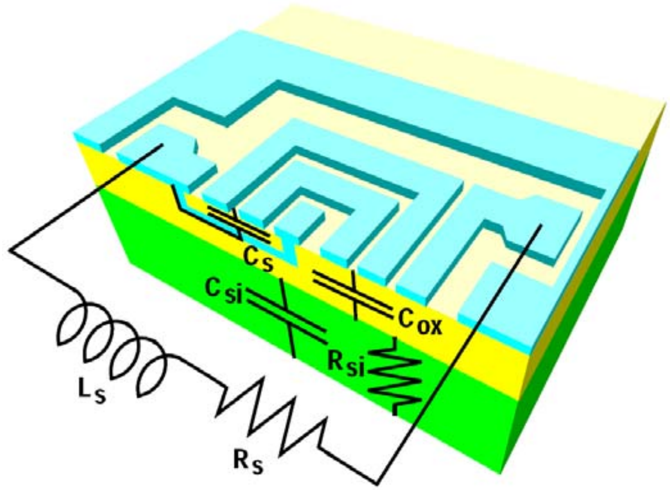
$$R_s \approx \frac{l}{\sigma w \delta (1 - e^{(\frac{-t}{\delta})})}$$

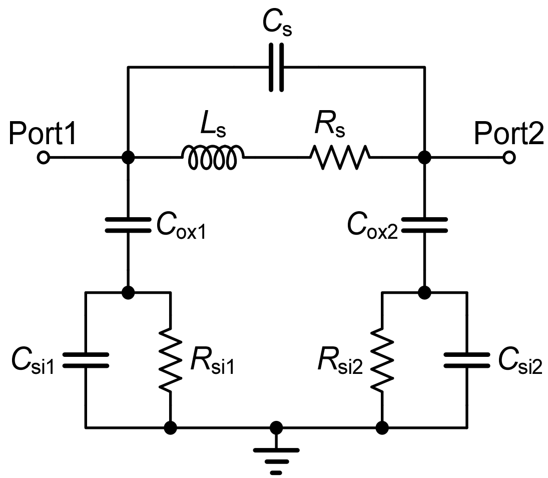
σ 是电导率，t为金属厚度

δ 是趋肤深度 $\delta = \sqrt{\dfrac{2}{\omega \mu_0 \sigma}}$

  - ❑ 金属－衬底间氧化层电容

$$C_{ox1} \approx C_{ox2} \approx \frac{1}{2}\frac{\varepsilon_{ox}}{t_{ox}} lw$$





9-元件精简集总电感模型

精简集总电路模型(II)

- 串通电容C_S

$$C_s \approx \frac{\varepsilon_{ox}}{t_{ox,M1-M2}} nw^2$$

- 衬底电容

$$C_{si1} \approx C_{si2} \approx \frac{1}{2} C_{sub} lw$$

- 衬底电阻

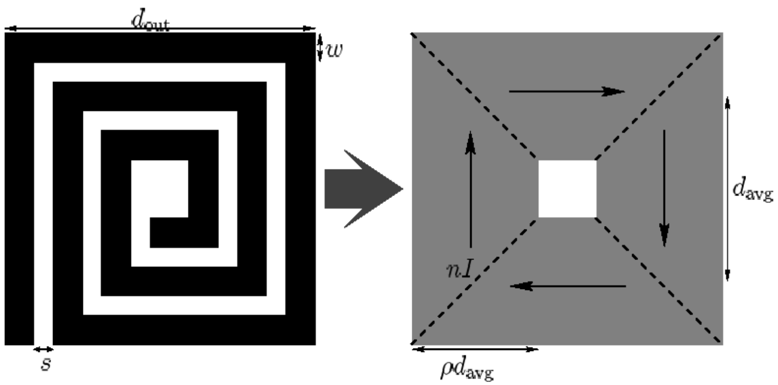
$$R_{si1} \approx R_{si2} \approx \frac{2}{G_{sub} lw}$$

平面螺旋电感的简单精确表达式(I)

- 电流块近似表达式
  - UC Berkeley, Mohan提出的

$$L_{cursh} = \frac{\mu n^2 d_{avg} c_1}{2}[\ln(c_2/\rho) + c_3\rho + c_4\rho^2]$$ μ是磁介质常数，n为圈数

$$d_{avg} = 0.5(d_{out} + d_{in}) \qquad \rho = (d_{out} - d_{in})/(d_{out} + d_{in})$$



电流块近似

Layout	c_1	c_2	c_3	c_4
Square	1.27	2.07	0.18	0.13
Hexagonal	1.09	2.23	0.00	0.17
Octagonal	1.07	2.29	0.00	0.19
Circle	1.00	2.46	0.00	0.20

电流块近似表达式中的系数

平面螺旋电感的简单精确表达式(II)

- 数据拟合多项式

❑数据拟合技术

$$L_{mon} = \beta d_{out}^{\alpha_1} \omega^{\alpha_2} d_{avg}^{\alpha_3} n^{\alpha_4} s^{\alpha_5}$$

Layout	β	α_1 (d_{out})	α_2 (w)	α_3 (d_{avg})	α_4 (n)	α_5 (s)
Square	$1.62 \cdot 10^{-3}$	-1.21	-0.147	2.40	1.78	-0.030
Hexagonal	$1.28 \cdot 10^{-3}$	-1.24	-0.174	2.47	1.77	-0.049
Octagonal	$1.33 \cdot 10^{-3}$	-1.21	-0.163	2.43	1.75	-0.049

多项式中的系数

❑如何拟合

所有变量采用对数形式表示

$$x_1 = \log d_{out} \quad x_2 = \log \omega \quad x_3 = \log d_{avg} \quad x_4 = \log n \quad x_5 = \log s$$

最小均方差拟合

目标函数:

$$\sum_{k=1}^{N} (y^{(k)} - \alpha_0 - \alpha_1 x_1^{(k)} - \alpha_2 x_2^{(k)} - \alpha_3 x_3^{(k)} - \alpha_4 x_4^{(k)} - \alpha_5 x_5^{(k)})^2$$

平面螺旋电感的简单精确表达式(II)

- 改进型Wheeler公式
  - ❑首先由H.Wheeler提出
  - ❑UC Berkeley，Mohan进行了改进

$$L_{mw} = K_1 \mu_0 \frac{n^2 d_{avg}}{1 + K_2 \rho}$$

系数K1和K2是与版图有关的系数，ρ 是填充系数

Layout	K_1	K_2
Square	2.34	2.75
Hexagonal	2.33	3.82
Octagonal	2.25	3.55

改进型Wheeler公式中的系数

优缺点

- 优点
  - ❑精简、集总电路模型，简单、通用且稳定
  - ❑具有物理意义
  - ❑非常容易与SPICE软件集成：电路仿真和优化的最佳选择
- 缺点
  - ❑模型与工作频率有关，不适合宽频带应用

等效电容的计算

- 什么是片上电感的等效电容?
  - ❑在自激频率点，磁场能力峰值与电场能量峰值相等
  - ❑给定电压峰值V_0，电场能量为 $C_{eq}V_0^2/2$
- 第一自激振荡频率f_{SR}

$$f_{SR} = \left(2\pi\sqrt{L_{eq}C_{eq}}\right)^{-1}$$

- 等效电容模型
  - ❑金属层间电容：$C_{M\text{-}M}$
  - ❑金属与衬底间电容：$C_{M\text{-}S}$

一些假设条件

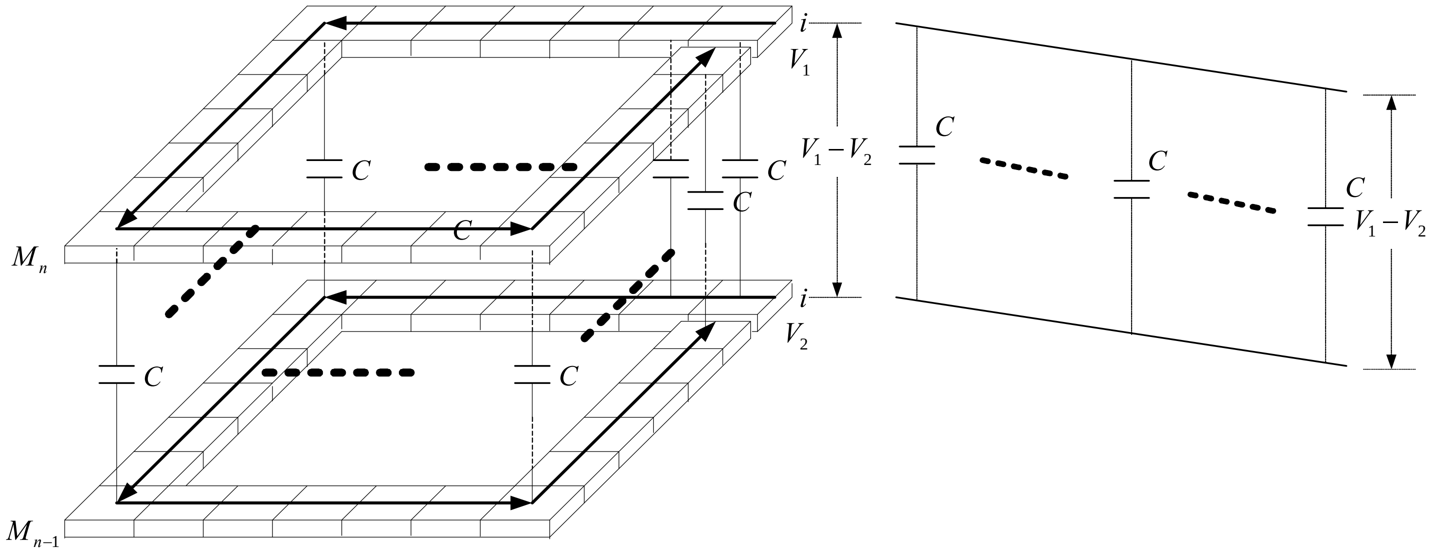
- 每圈线圈的几何参数是相同的
  - 宽度：**w**
  - 厚度：**t**
  - 长度：**l**
- 每圈线圈的电学参数是相同的
  - 金属电导率：ρ
  - 电流：**i**

金属层间电容：C_{M-M}

- 电场能量

$$E_{e,C_m}=\frac{1}{2}C_mV_{C_m}^2=\frac{1}{2}\frac{C_{M_n-M_{n-1}}wl}{N}(V_1-V_2)^2$$

$$E_{e,C}=\sum_{m=1}^{N}E_{e,C_m}=\sum_{m=1}^{N}\frac{1}{2}C_mV_{C_m}^2=\frac{1}{2}C_{M_n-M_{n-1}}wl(V_1-V_2)^2$$



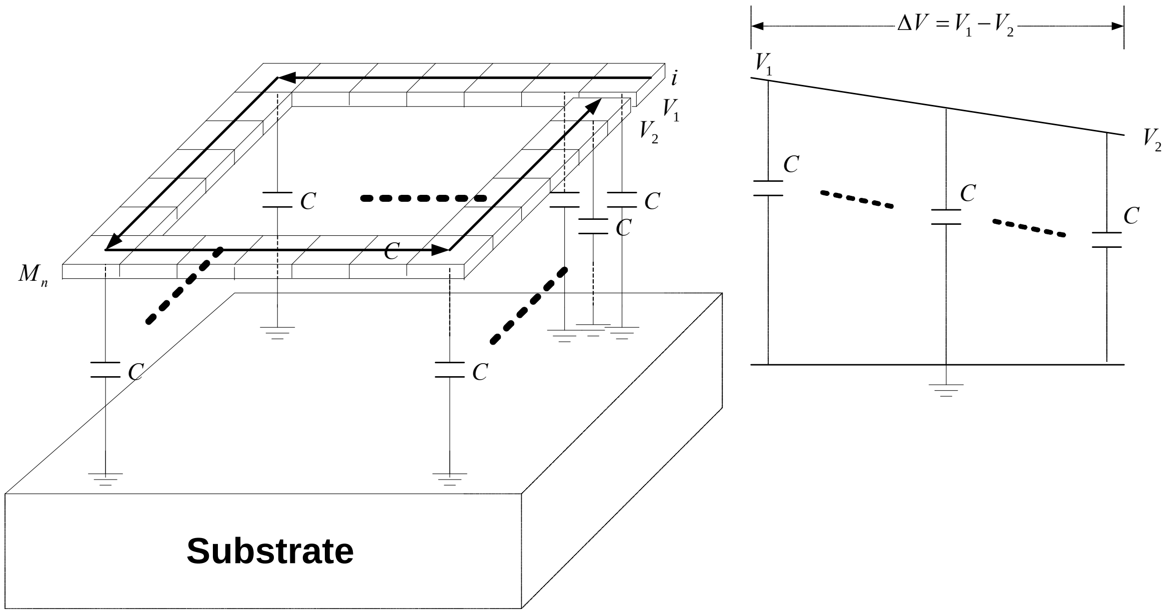
金属层间的分布电容和电压压降图

金属与衬底间电容：$C_{M\text{-}S}$

- 电场能量

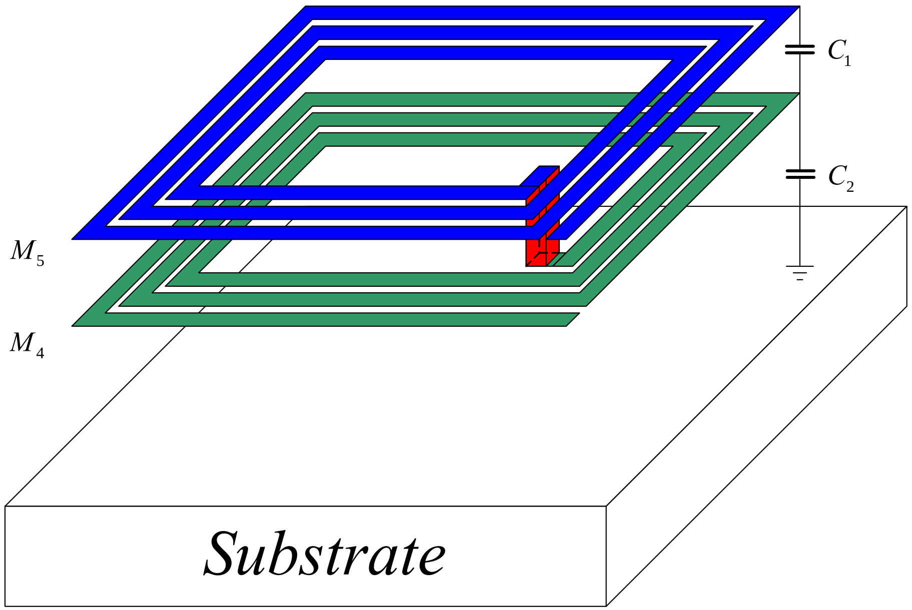
$$E_{e,C_m} = \frac{1}{2}C_m V_{C_m}^2 = \frac{1}{2}\frac{C_{M_n-S}wl}{N}\left(V_1 - \frac{m}{N}\Delta V\right)^2$$

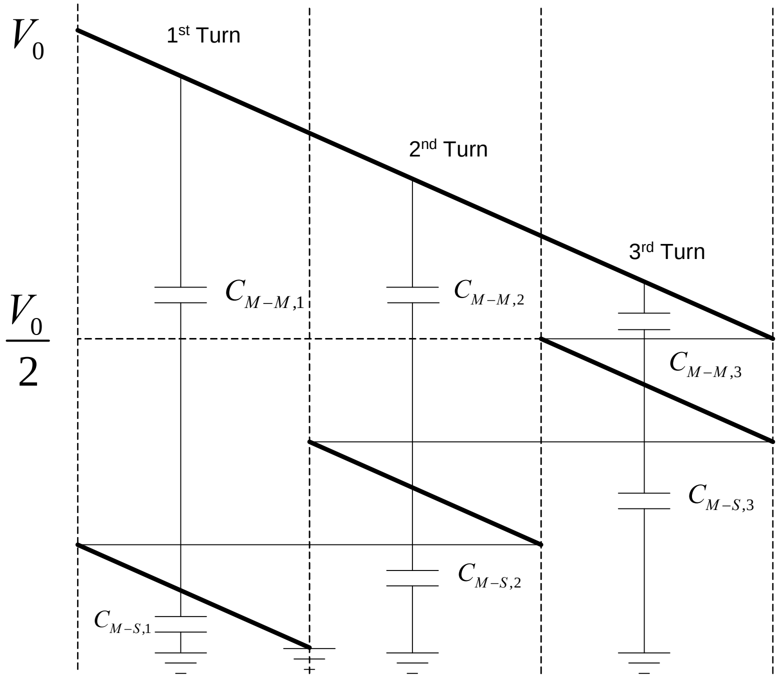
$$E_{e,C} = \sum_{m=1}^{N} E_{e,C_m} = \sum_{m=1}^{N}\frac{1}{2}C_m V_{C_m}^2 = \sum_{m=1}^{N}\frac{1}{2}\frac{C_{M_n-S}wl}{N}\left(V_1 - \frac{m}{N}\Delta V\right)^2 \overset{N\to\infty}{\approx} \frac{1}{6}C_{M_n-S}wl\left\{V_1^2 + V_2^2 + V_1V_2\right\}$$



金属与衬底间的分布电容和电压压降图

叠成电感(Stacked)的等效电容





n圈2层叠成电感和电压压降图

电容系数

- K1为金属间电容系数
- K2为金属与衬底间电容系数

$$C_{eq} = \kappa_1 C_1 + \kappa_2 C_2$$

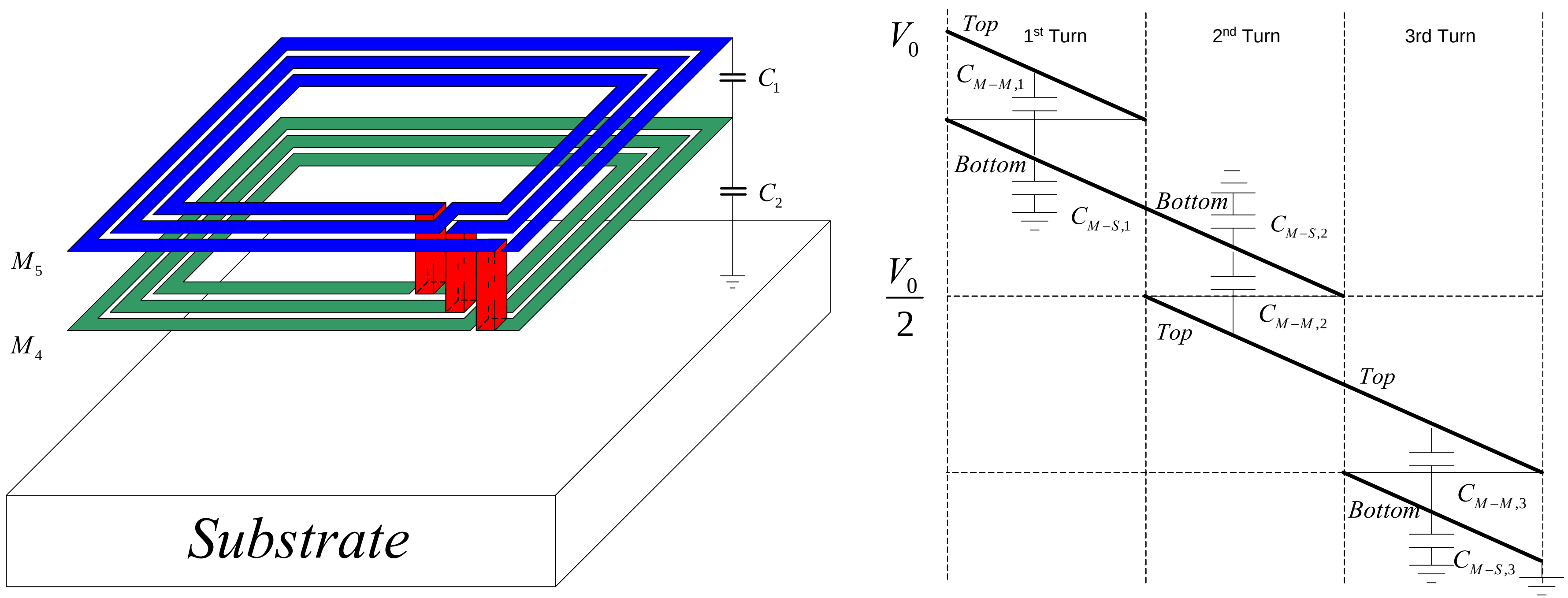
$$C_1 = C_{M_n - M_{n-1}} w \cdot \sum_{k=1}^{n} l_k \quad C_2 = C_{M_n - S} w \cdot \sum_{k=1}^{n} l_k \quad l_k = N \cdot tg(\frac{\pi}{N})[d_{in}^{'} + 2(n-k)p]$$

$$\rho_p = p / d_{in}^{'} = (w+s) \big/ d_{in}^{'}$$

$$\kappa_1 = \frac{1}{\left(n\left[1+(n-1)\rho_p\right]\right)^3} \sum_{m=1}^{n} \left[1+2(n-m)\rho_p\right]\left((n-m+\frac{1}{2})+(n-m)^2 \rho_p\right)^2$$

$$\kappa_2 = \frac{1}{12}$$

3D叠成电感的等效电容



n圈2层3D叠成电感和电压压降图

电容等效系数

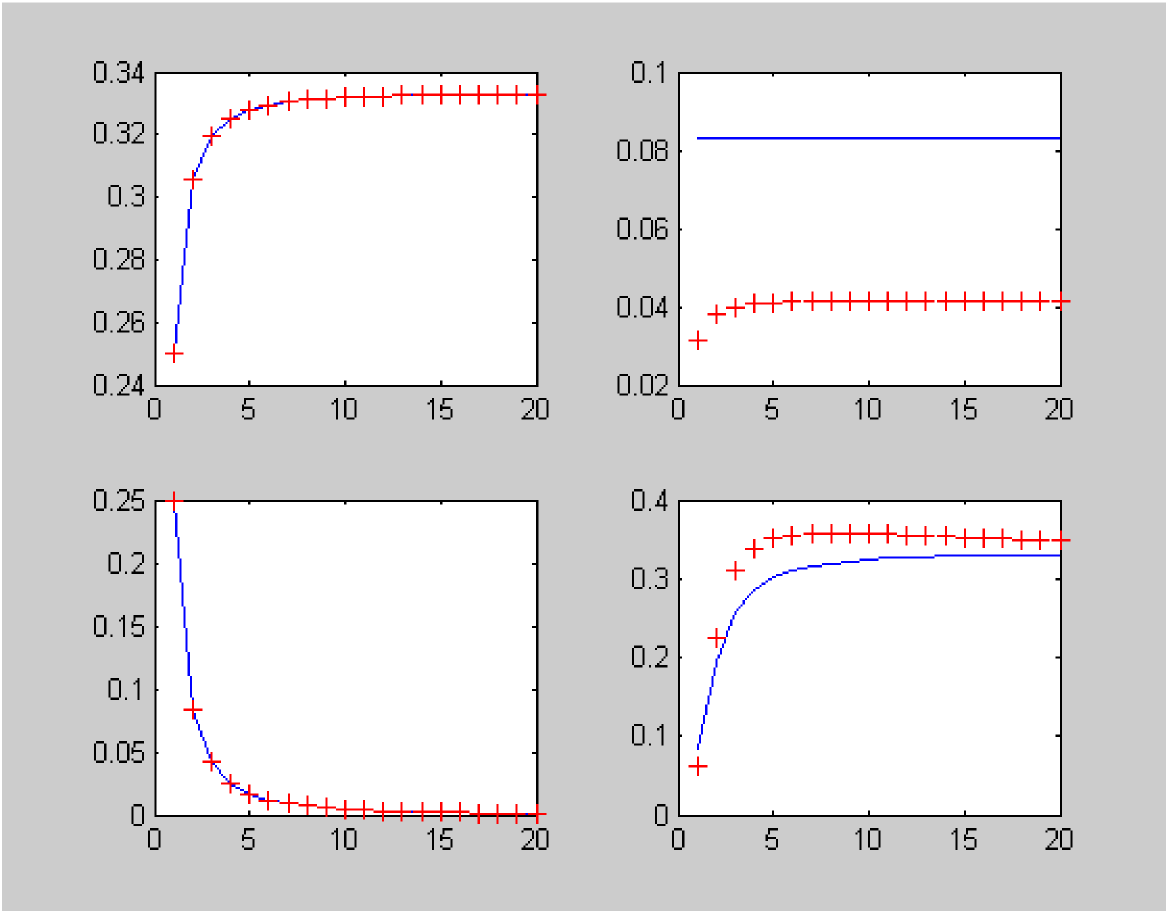
$$\kappa_1 = \frac{1}{4}\sum_{m=1}^{n}\left(\frac{l_m}{2\sum_{k=1}^{n} l_k}\right)^3 = \frac{1}{4}\sum_{m=1}^{n}\left(\frac{d_{in}^{'} + 2(n-m)p}{n\left[d_{in}^{'} + (n-1)p\right]}\right)^3$$

$$\begin{aligned}\kappa_2 = \frac{1}{12\left(n\left[1+(n-1)\rho_p\right]\right)^3}\sum_{m=1}^{n}\left(1+2(n-m)\rho_p\right)\Bigg\{&\left(2\left(n-m+1+\frac{\left[-1+(-1)^m\right]}{4}\right)+(n-m)\left(2n-2m+1+(-1)^m\right)\rho_p\right)^2\\
&+\left(2\left(n-m+\frac{\left[1+(-1)^m\right]}{4}\right)+(n-m)\left(2n-2m-1+(-1)^m\right)\rho_p\right)^2+\Bigg(2\left(n-m+1+\frac{\left[-1+(-1)^m\right]}{4}\right)+\\
&(n-m)\left(2n-2m+1+(-1)^m\right)\rho_p\Bigg)\left(2\left(n-m+\frac{\left[1+(-1)^m\right]}{4}\right)+(n-m)\left(2n-2m-1+(-1)^m\right)\rho_p\right)\Bigg\}\end{aligned}$$

比较

κ_1　　　　κ_2

Stacked
叠成电感



3D叠成电感

叠成电感的特点

- 高自激振荡频率
- 面积小

提高品质因数的几种方法

- 电场地屏蔽层
- 多路径分割
- 深阱双反偏pn结隔离

图1 电场地屏蔽层

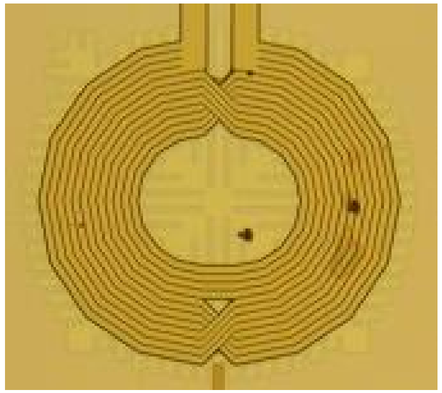


图2 多路径分割

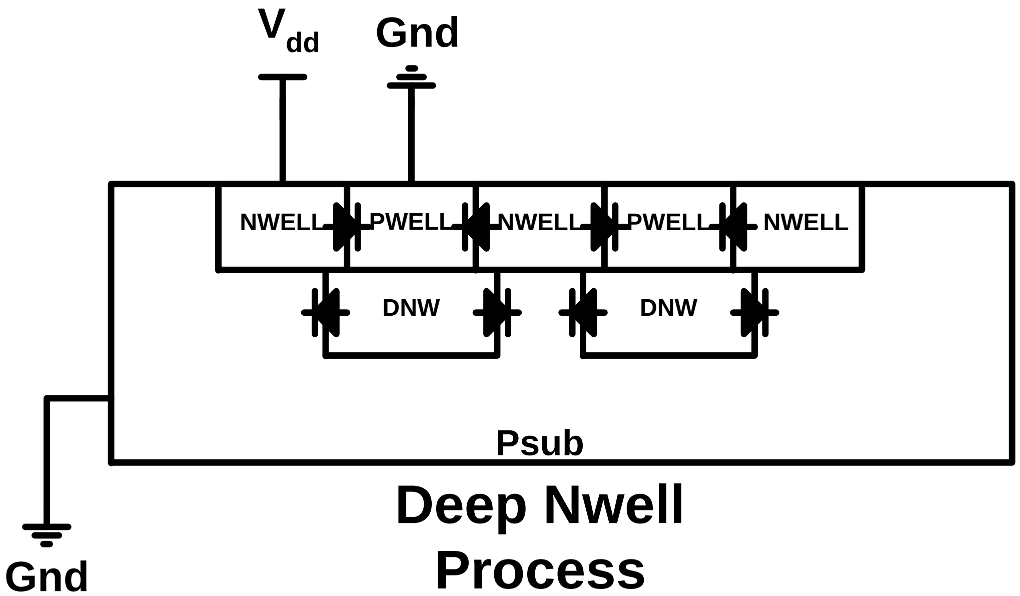
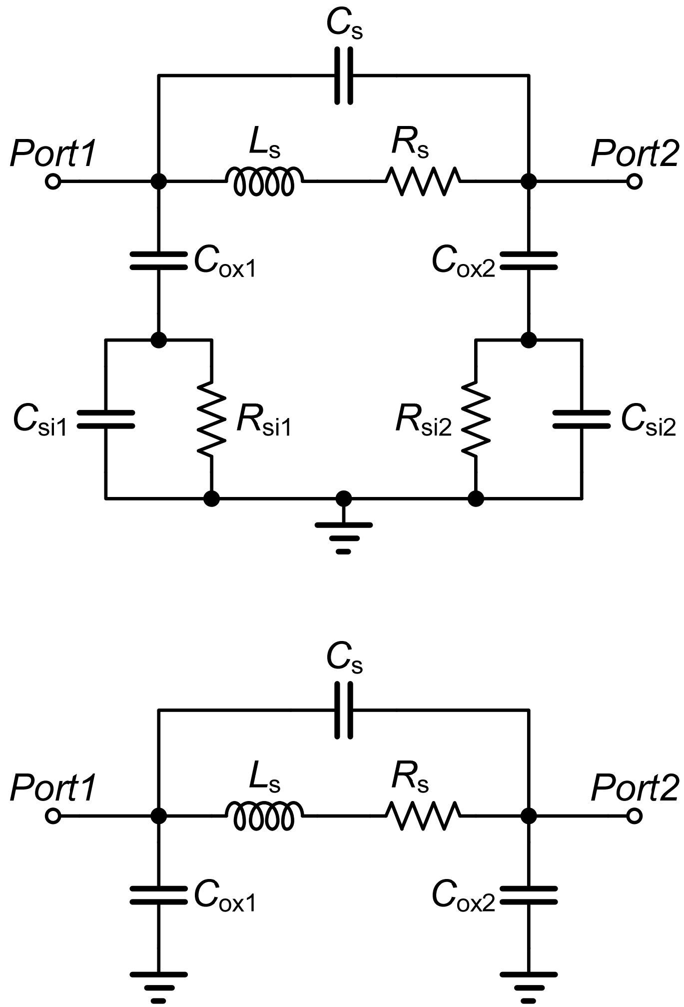


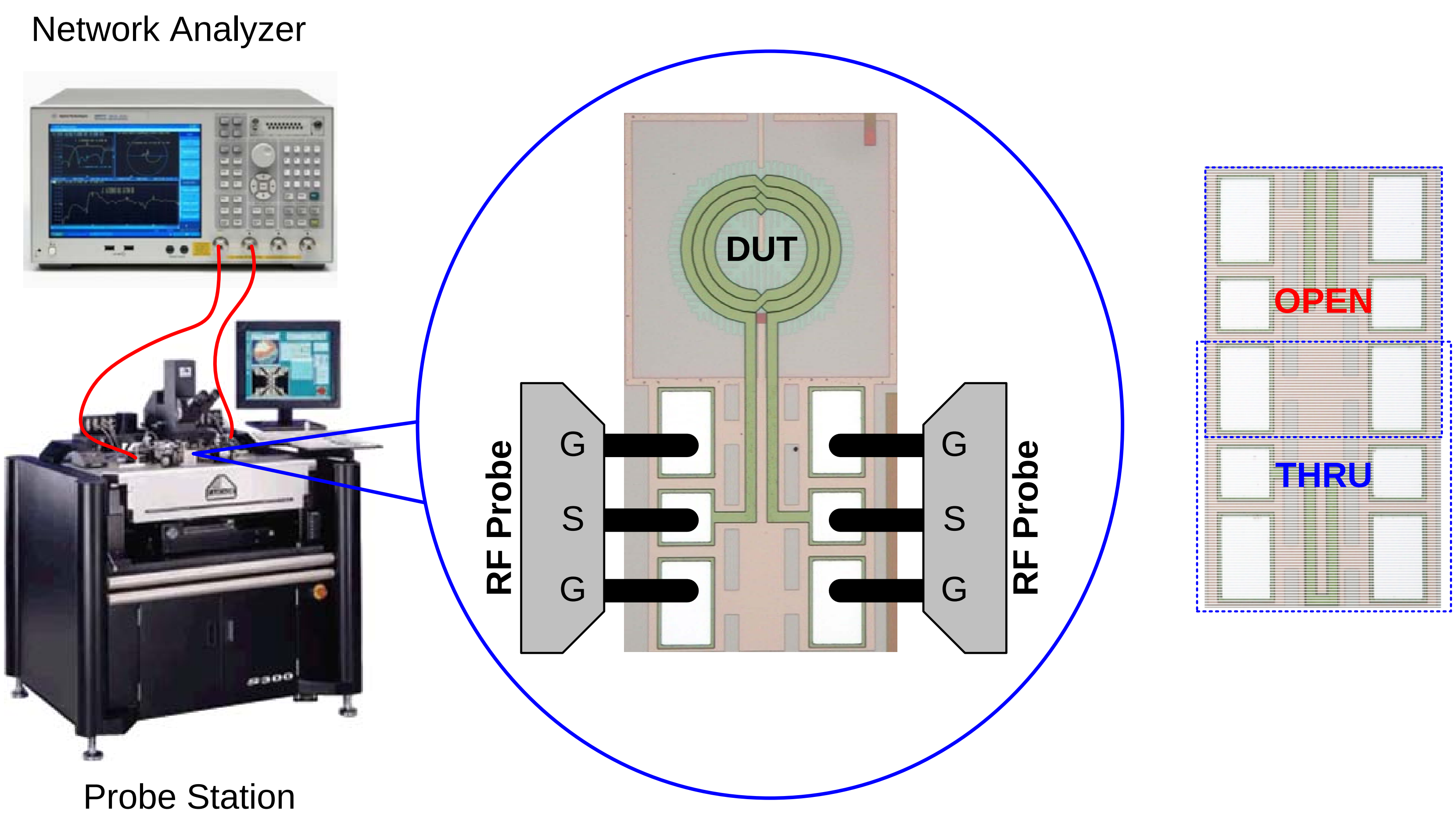
图3 深阱双反偏PN结隔离

PGS地屏蔽层结构

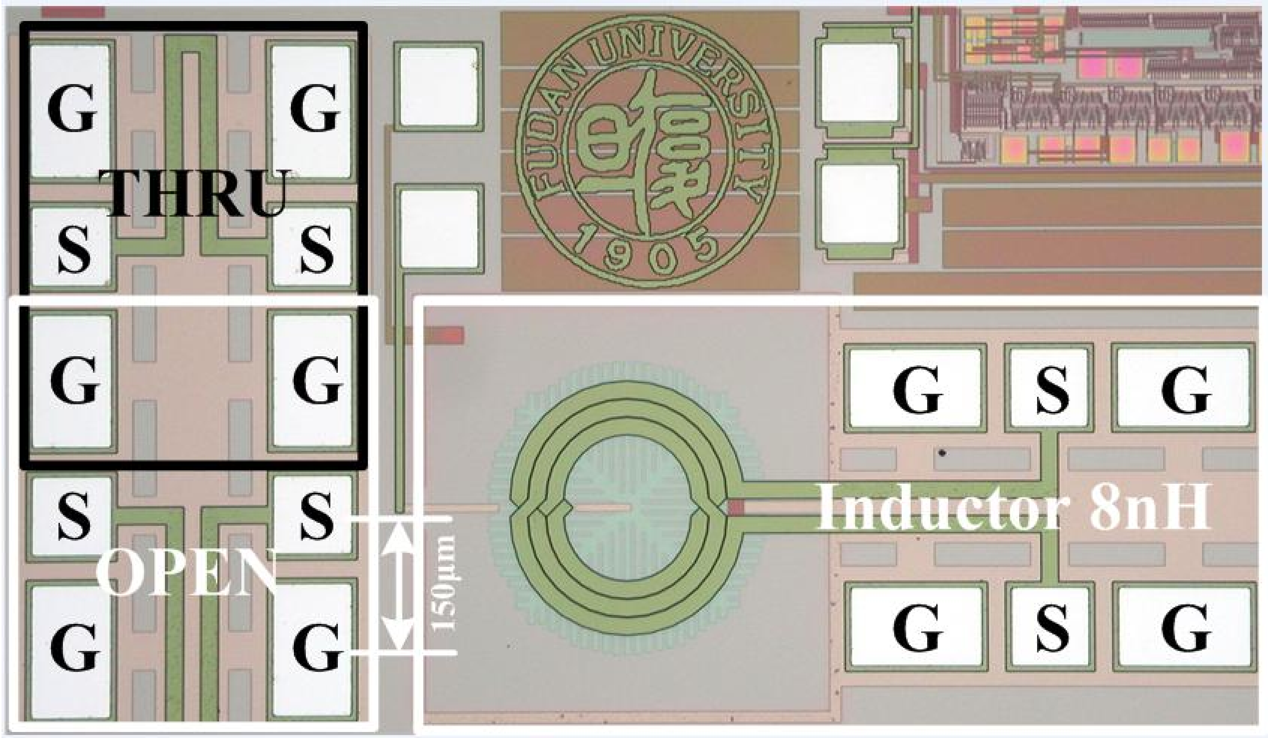


PGS Groud shielded substrate loss

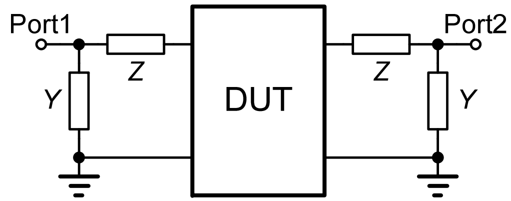
片上电感的在片测试

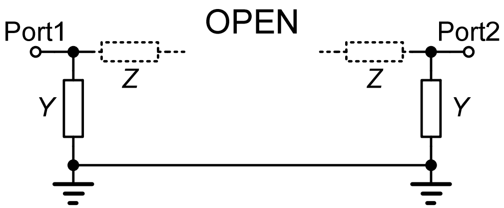

Network Analyzer
DUT
G
S
G
RF Probe
G
S
G
RF Probe
OPEN
THRU
Probe Station

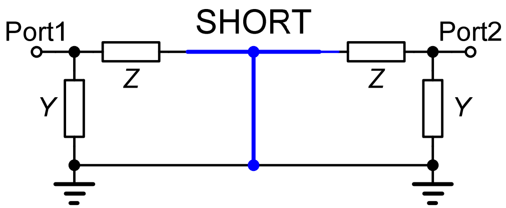
去嵌入结构和方法

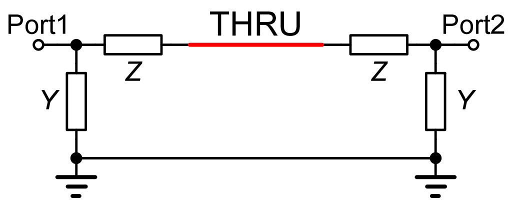


- 去嵌入的作用去除以下寄生参数
  - ❑ 探针接触电阻
  - ❑ PAD寄生电容
  - ❑ 连接线电阻

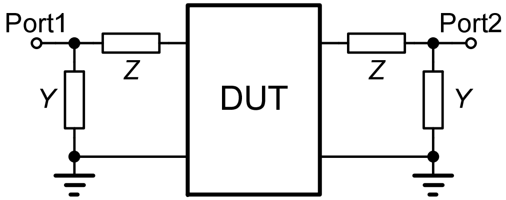


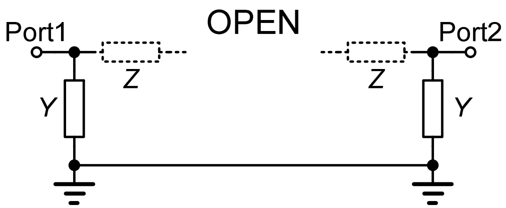


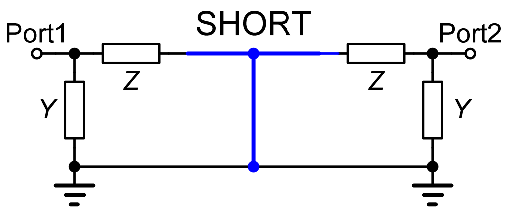




OPEN-SHORT去嵌入

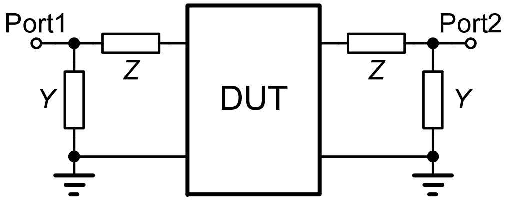


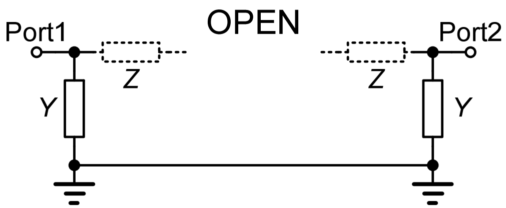


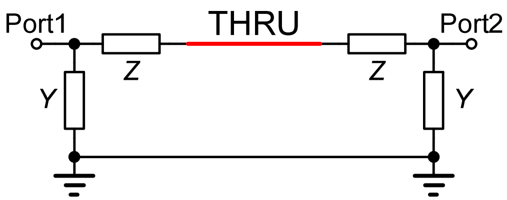


OPEN-SHORT去嵌入步骤	
第一步	S参数转换为Y参数 $S_{\text{meas,DUT}} \rightarrow Y_{\text{meas,DUT}}$ $S_{\text{meas,SHORT}} \rightarrow Y_{\text{meas,SHORT}}$ $S_{\text{meas,OPEN}} \rightarrow Y_{\text{meas,OPEN}}$
第二步	DUT和SHORT结构去除PAD并联寄生电容 $Y_{\text{meas,DUT}} - Y_{\text{meas,OPEN}} \rightarrow Y_{\text{DUT-OPEN}}$ $Y_{\text{meas,SHORT}} - Y_{\text{meas,OPEN}} \rightarrow Y_{\text{SHORT-OPEN}}$
第三步	Y参数转换为Z参数 $Y_{\text{DUT-OPEN}} \rightarrow Z_{\text{DUT-OPEN}}$ $Y_{\text{SHORT-OPEN}} \rightarrow Z_{\text{SHORT-OPEN}}$
第四步	去除寄生串联电阻 $Z_{\text{DUT-OPEN}} - Z_{\text{SHORT-OPEN}} \rightarrow Z_{\text{DUT}}$
第五步	Z参数转换为S参数 $Z_{\text{DUT}} \rightarrow S_{\text{DUT}}$

OPEN-THRU去嵌入





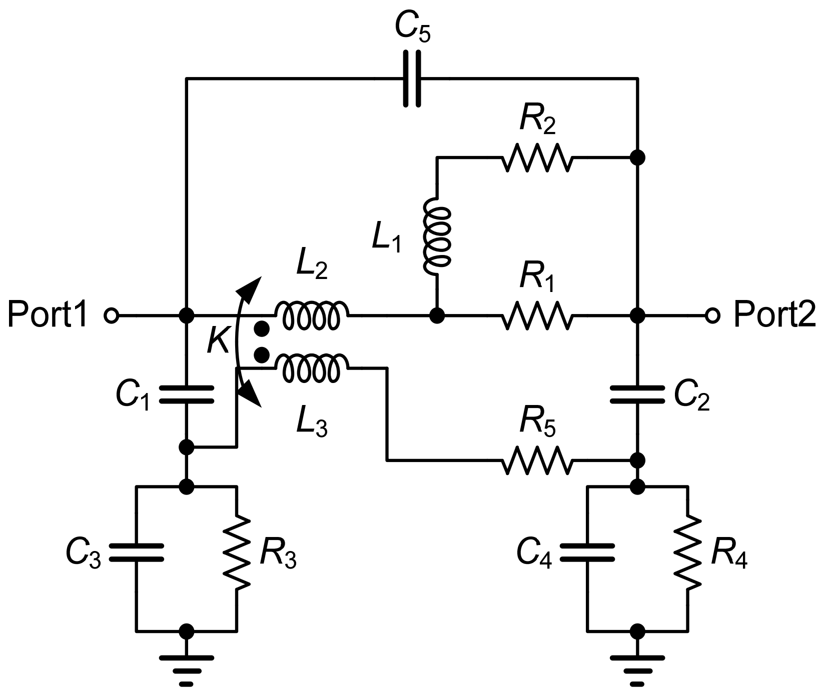


OPEN-THRU去嵌入步骤	
第一步	S参数转换为Y参数 $S_{\text{meas,DUT}} \rightarrow Y_{\text{meas,DUT}}$ $S_{\text{meas,THR}} \rightarrow Y_{\text{meas,THRU}}$ $S_{\text{meas,OPEN}} \rightarrow Y_{\text{meas,OPEN}}$
第二步	DUT和SHORT结构去除PAD寄生并联电容 $Y_{\text{meas,DUT}} - Y_{\text{meas,OPEN}} \rightarrow Y_{\text{DUT-OPEN}}$ $Y_{\text{meas,THRU}} - Y_{\text{meas,OPEN}} \rightarrow Y_{\text{THRU-OPEN}}$
第三步	Y参数转换为Z参数 $Y_{\text{DUT-OPEN}} \rightarrow Z_{\text{DUT-OPEN}}$ $Y_{\text{THRU-OPEN}} \rightarrow Z_{\text{THRU-OPEN}}$
第四步	去除寄生串联电阻 $Z_{\text{DUT-OPEN}} - \begin{bmatrix} \dfrac{1}{2Y_{11,\text{THRU-OPEN}}} & 0 \\ 0 & \dfrac{1}{2Y_{22,\text{THRU-OPEN}}} \end{bmatrix} \rightarrow Z_{\text{DUT}}$
第五步	Z参数转换为S参数 $Z_{\text{DUT}} \rightarrow S_{\text{DUT}}$

宽频带电感模型

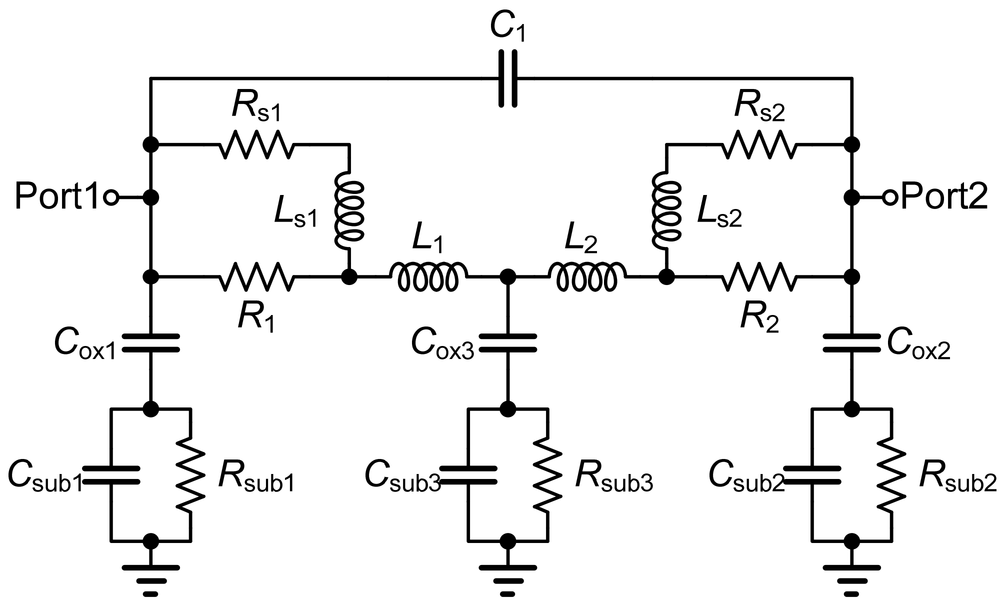
单 π 宽带模型

[J. Kino, VLSI Symp. 2004]



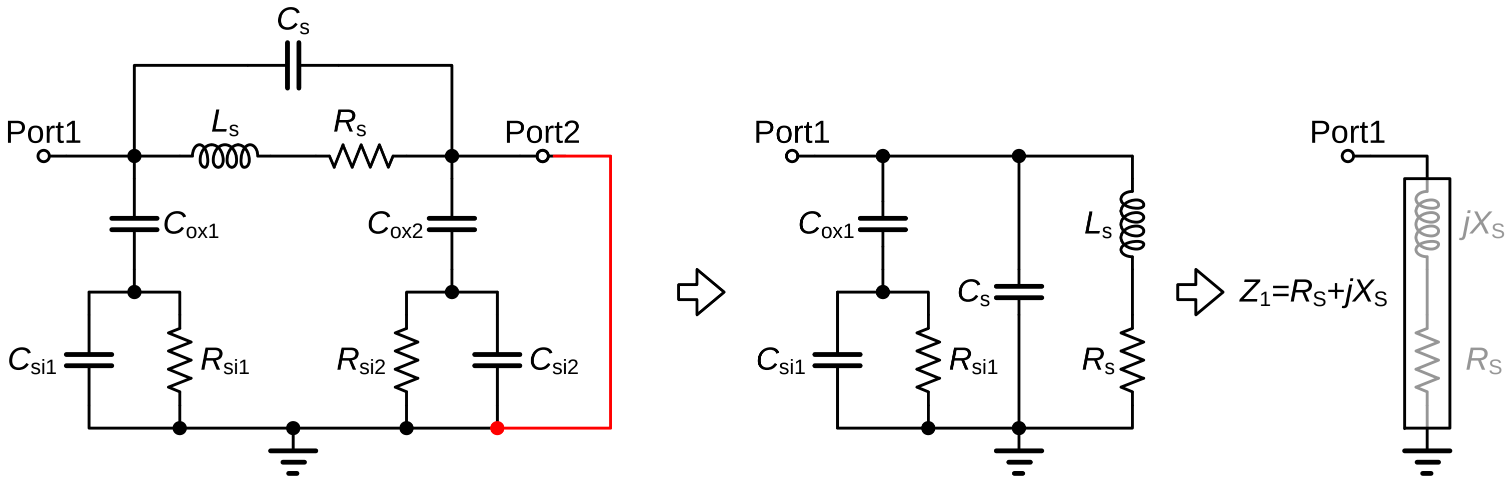
双 π 宽带模型

[Y. Cao, JSSC. March 2003]



RLQ单端等效参数提取(I)

- 单端口阻抗模型：端口1或者端口2接地



$$Z_1 = Z_0\left(\frac{1+S_{11}}{1-S_{11}}\right)$$

- 等效单端串联电感L_s

$$L_s = \frac{\mathrm{Im}(Z_1)}{2\pi f}$$

- 等效单端串联电阻R_s

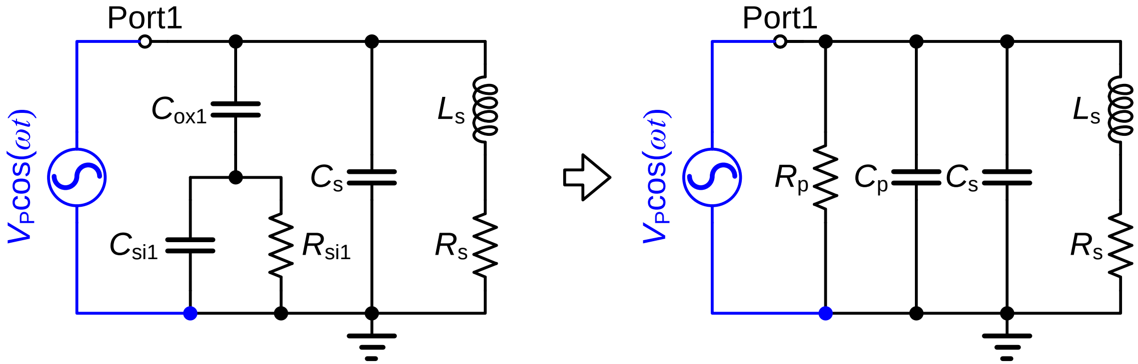
$$R_s = \mathrm{Re}(Z_1)$$

- 单端串联品质因数Q_{se}

$$Q_{se} = \frac{\mathrm{Im}(Z_1)}{\mathrm{Re}(Z_1)}$$

单端串联品质因数

$$\frac{1}{j\omega C_{ox1}}+\frac{\frac{1}{j\omega C_{ox1}}R_{si1}}{\frac{1}{j\omega C_{ox1}}+R_{si1}}=\frac{\frac{1}{j\omega C_p}R_p}{\frac{1}{j\omega C_p}+R_p}$$



$$R_p=\frac{1}{\omega^2C_{ox}^2R_{si1}}+R_{si1}\left(\frac{C_{ox}+C_{si1}}{C_{ox}}\right)^2$$

$$C_p=C_{ox}\frac{1+\omega^2\left(C_{ox}+C_{si1}\right)C_{si1}R_{si1}^2}{1+\omega^2\left(C_{ox}+C_{si1}\right)^2R_{si1}^2}$$

$$E_{\text{peak,magnetic}}=\frac{I_{\text{peak}}^2L_s}{2}=\frac{V_{\text{peak}}^2L_s}{2\left[\left(\omega L_s\right)^2+R_s^2\right]}$$

$$E_{\text{peak,electric}}=\frac{\left(C_p+C_s\right)V_{\text{peak}}^{\ 2}}{2}=\frac{V_P^{\ 2}\left(C_p+C_s\right)}{2}$$

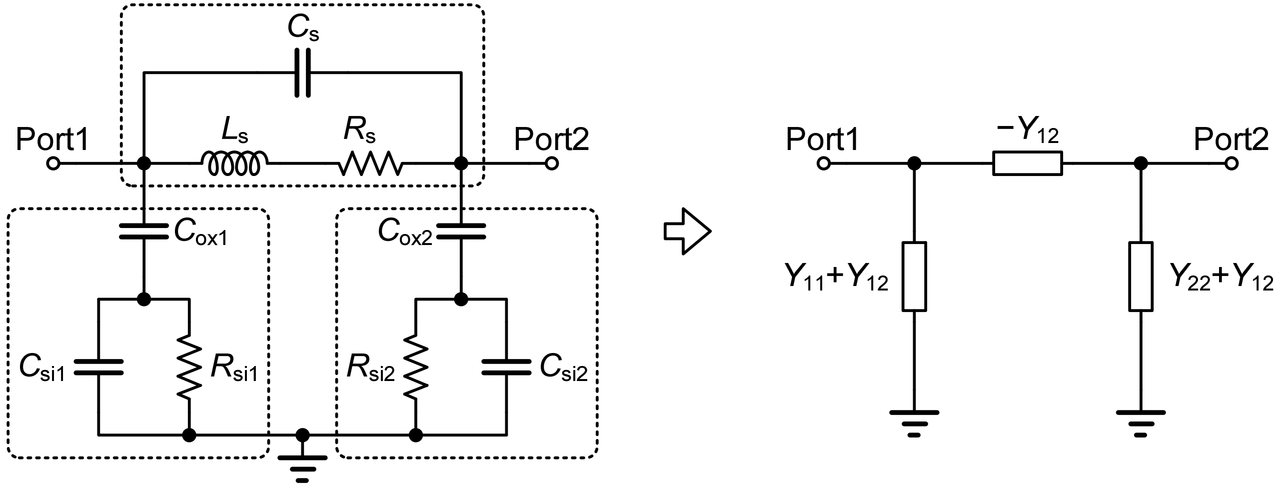
$$E_{\text{loss in one oscillation cycle}}=\frac{2\pi}{\omega}\cdot\frac{V_P^2}{2}\cdot\left[\frac{1}{R_p}+\frac{R_s}{\left(\omega L_s\right)^2+R_s^2}\right]$$

$$Q_{se}=2\pi\frac{E_{\text{peak,magnetic}}-E_{\text{peak,electric}}}{E_{\text{loss in one oscillation cycle}}}$$

$$=\overbrace{\frac{\omega L_s}{R_s}}^{Q_{LF}}\times\overbrace{\frac{R_p}{R_p+\left[\left(\omega L_s/R_s\right)^2+1\right]R_s}}^{k_{SL}}\times\underbrace{\left[1-\frac{R_s^2\left(C_s+C_p\right)}{L_s}-\omega^2L_s\left(C_s+C_p\right)\right]}_{k_{SR}}$$

RLQ单端等效参数提取(II)

- 双端口单 π Y模型

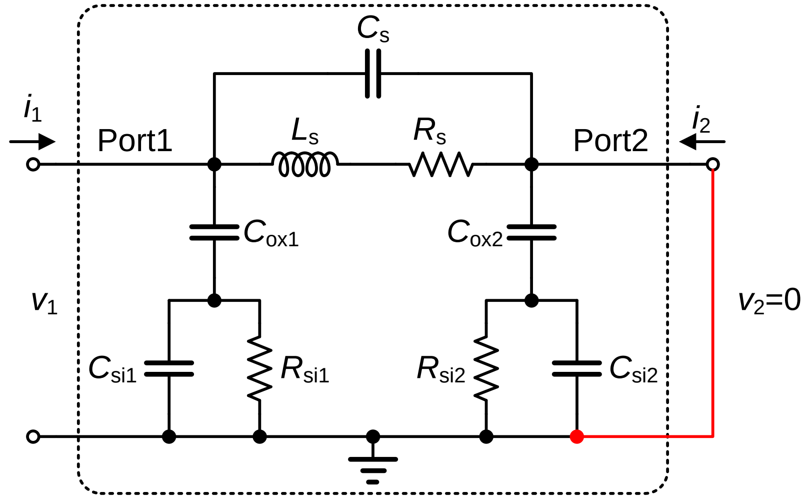


- 等效单端串联电感L_s $$L_s = \frac{\mathrm{Im}(1/Y_{11})}{2\pi f} \quad or \quad L_s = \frac{\mathrm{Im}(-1/Y_{12})}{2\pi f}$$
- 等效单端串联电阻R_s $$R_s = \mathrm{Re}(1/Y_{11}) \quad or \quad R_s = \mathrm{Re}(-1/Y_{12})$$
- 单端串联品质因数Q_{se} $$Q_{se} = \frac{\mathrm{Im}(1/Y_{11})}{\mathrm{Re}(1/Y_{11})}$$

RLQ单端等效参数提取(III)

- 双端口Z模型

$$\begin{bmatrix} v_1 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \quad i_2 = -\frac{Z_{21}}{Z_{22}} i_1$$



$$Z_{port1} = Z_{11} - \frac{Z_{12}Z_{21}}{Z_{22}}$$

$$Z_{port2} = Z_{22} - \frac{Z_{12}Z_{21}}{Z_{11}}$$

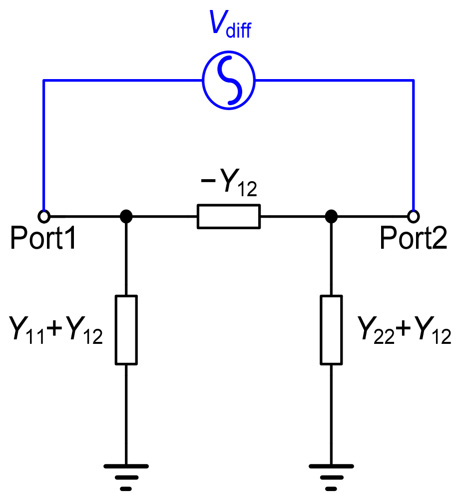
- 等效单端串联电感L_s $\quad L_{s,port1,2} = \mathrm{Im}(Z_{port1,2})/2\pi f$
- 等效单端串联电阻R_s $\quad R_{s,port1,2} = \mathrm{Re}(Z_{port1,2})$
- 单端串联品质因数Q_{se} $\quad Q_{se,port1,2} = \dfrac{\mathrm{Im}(Z_{port1,2})}{\mathrm{Re}(Z_{port1,2})}$

RLQ差分等效参数提取(I)

- 差分激励Y参数

$$Z_{\text{diff}} = \left(-\frac{1}{Y_{12}}\right) \Bigg\| \left(\frac{1}{Y_{11}+Y_{12}} + \frac{1}{Y_{22}+Y_{12}}\right)$$

$$= \frac{Y_{11}+Y_{22}+2Y_{12}}{Y_{11}Y_{22}-Y_{12}^2}$$



- 等效差分串联电感L_s

$$L_s = \frac{\operatorname{Im}(Z_{\text{diff}})}{2\pi f}$$

- 等效差分串联电阻R_s

$$R_s = \operatorname{Re}(Z_{\text{diff}})$$

- 差分串联品质因数Q_{diff}

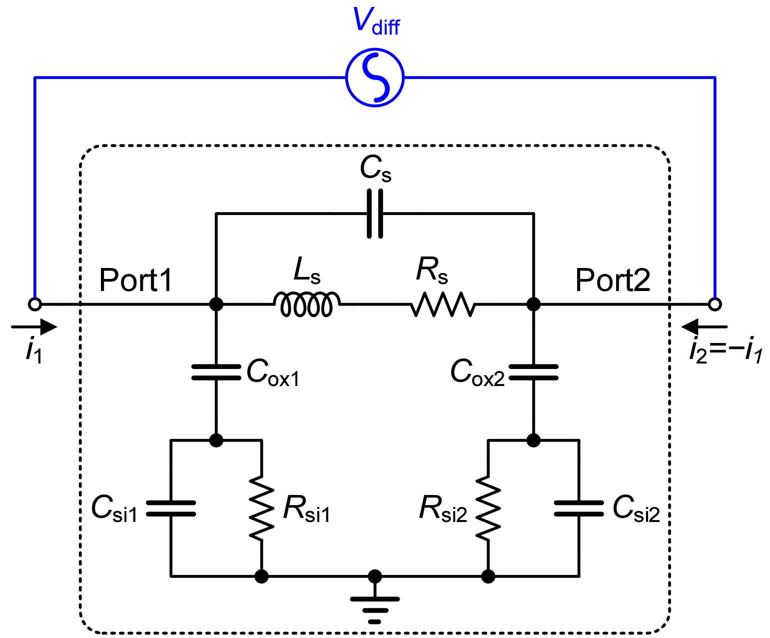
$$Q_{\text{diff}} = \frac{\operatorname{Im}(Z_{\text{diff}})}{\operatorname{Re}(Z_{\text{diff}})}$$

RLQ差分等效参数提取(II)

- 差分激励Z参数

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ -i_1 \end{bmatrix}$$

$$Z_{\mathrm{diff}} = \frac{V_1 - V_2}{i_1} = Z_{11} + Z_{22} - Z_{12} - Z_{21}$$



- 等效差分串联电感L_s

$$L_s = \frac{\mathrm{Im}(Z_{\mathrm{diff}})}{2\pi f}$$

- 等效差分串联电阻R_s

$$R_s = \mathrm{Re}(Z_{\mathrm{diff}})$$

- 差分串联品质因数Q_{diff}

$$Q_{\mathrm{diff}} = \frac{\mathrm{Im}(Z_{\mathrm{diff}})}{\mathrm{Re}(Z_{\mathrm{diff}})}$$

RLQ差分等效参数提取(III)

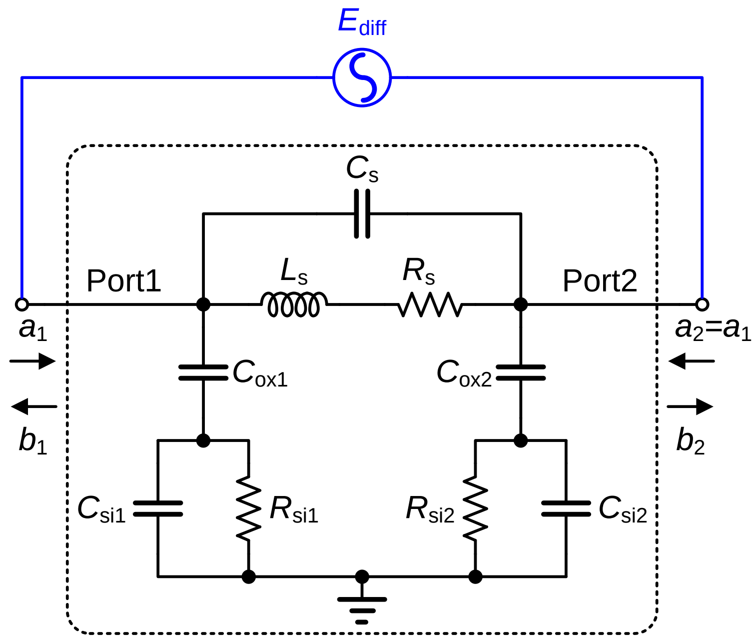
- 差分激励S参数

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

$$S_{\text{diff}} = \frac{b_1 - b_2}{a_1 - a_2} = \frac{(S_{11} + S_{22} - S_{12} - S_{21})a}{2a}$$

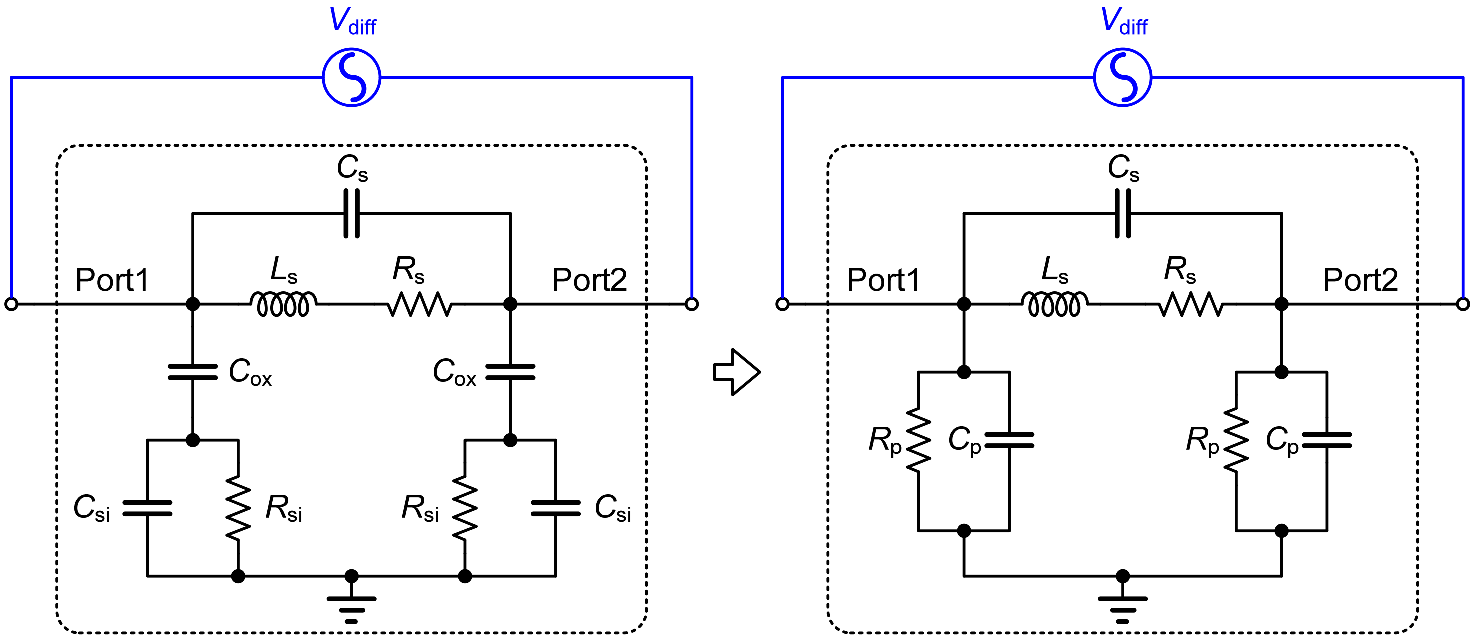
$$= \frac{S_{11} + S_{22} - S_{12} - S_{21}}{2}$$

$$Z_{\text{diff}} = 2Z_0 \frac{1 + S_{\text{diff}}}{1 - S_{\text{diff}}}$$



- 等效差分串联电感L_s $\quad L_s = \mathrm{Im}(Z_{\text{diff}})/2\pi f$
- 等效差分串联电阻R_s $\quad R_s = \mathrm{Re}(Z_{\text{diff}})$
- 差分串联品质因数Q_{diff} $\quad Q_{\text{diff}} = \dfrac{\mathrm{Im}(Z_{\text{diff}})}{\mathrm{Re}(Z_{\text{diff}})}$

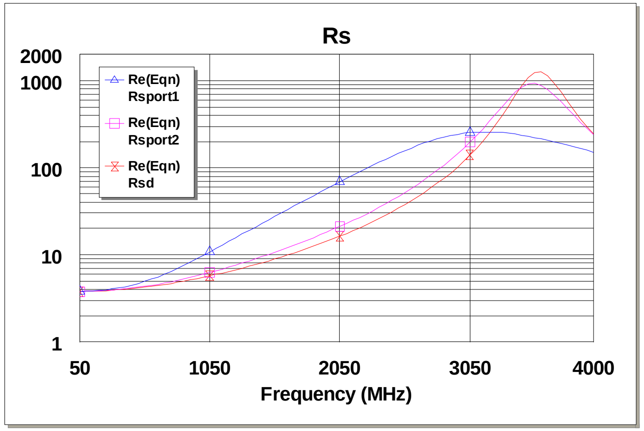
差分串联品质因数

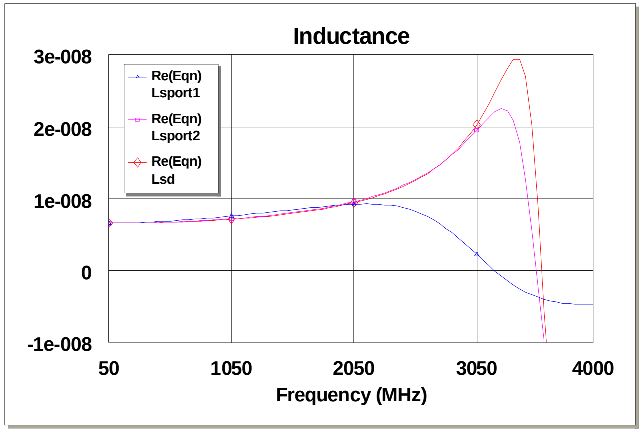


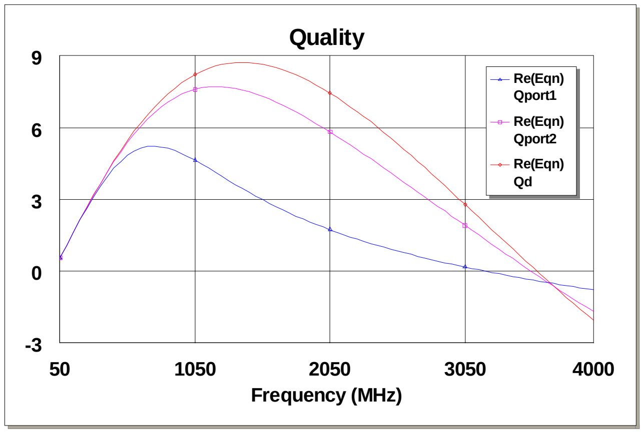
$$Q_{\mathrm{diff}} = 2\pi \frac{E_{\text{peak,magnetic}} - E_{\text{peak,electric}}}{E_{\text{loss in one oscillation cycle}}}$$

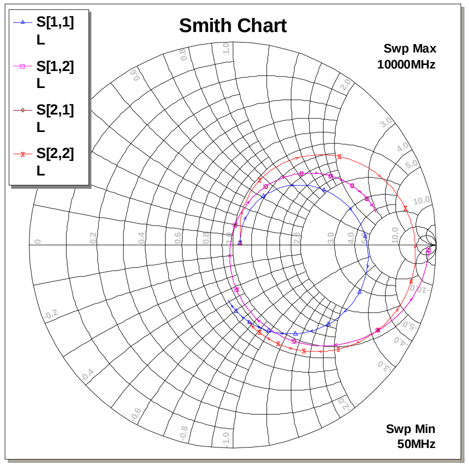
$$= \overbrace{\frac{\omega L_s}{R_s}}^{Q_{LF}} \times \overbrace{\frac{\boxed{2R_p}}{\boxed{2R_p} + \left[\left(\omega L_s / R_s\right)^2 + 1\right] R_s}}^{k_{SL}} \times \overbrace{\left[1 - \frac{R_s^2\left(C_s + \boxed{C_p/2}\right)}{L_s} - \omega^2 L_s\left(C_s + \boxed{C_p/2}\right)\right]}^{k_{SR}}$$

非对称电感RLQS曲线

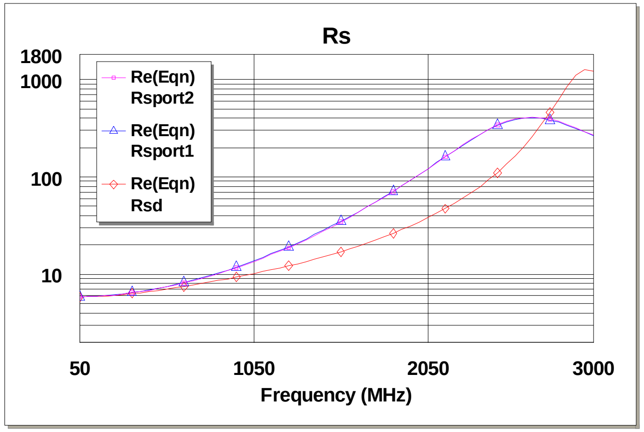


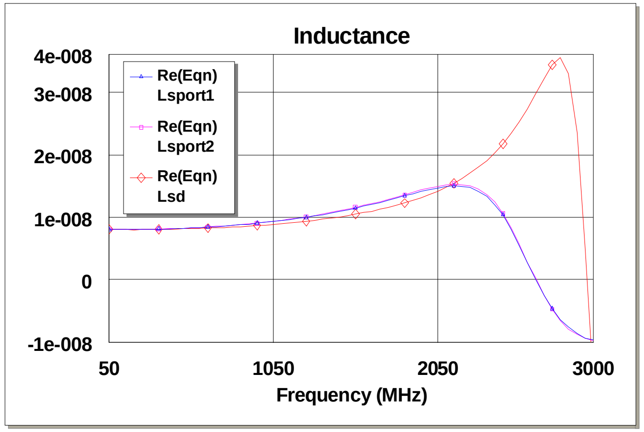


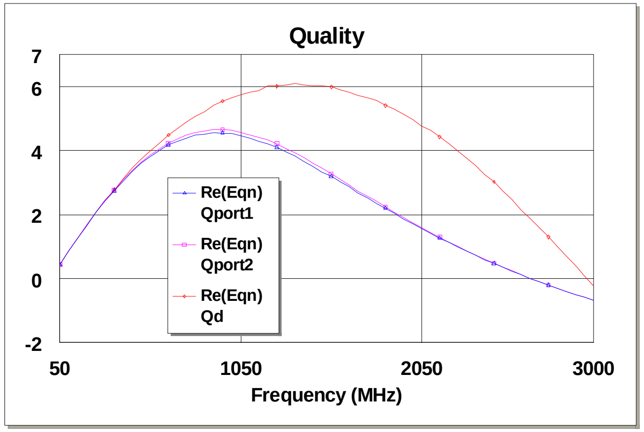


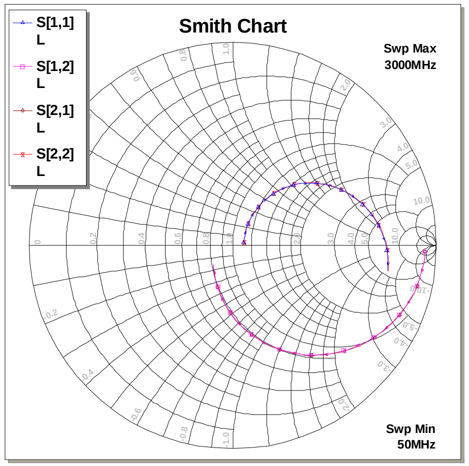


对称差分电感RLQS曲线







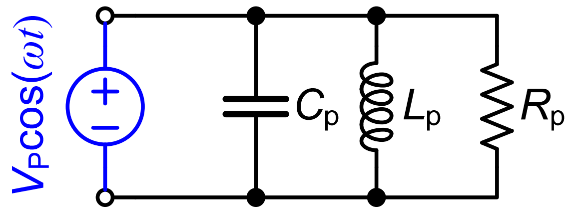


RLC并联谐振网络品质因数

- 电感Q值

$$Q_L = 2\pi \frac{E_{\text{peak,magnetic}} - E_{\text{peak,electric}}}{E_{\text{loss in one oscillation cycle}}} = 2\pi \frac{\dfrac{V_P^2}{2\omega^2 L_p} - \dfrac{C_p V_P^2}{2}}{\dfrac{2\pi}{\omega}\cdot\dfrac{V_P^2}{2R_p}}$$

$$= \omega C_p R_p \left[\left(\frac{\omega_0}{\omega}\right)^2 - 1\right] = \frac{R_p}{\omega L_p}\left[1 - \left(\frac{\omega}{\omega_0}\right)^2\right]$$



$$E_{\text{peak,magnetic}} = \frac{I_{\text{peak}}^2 L_p}{2} = \frac{V_P^2}{2\omega^2 L_p} = 2E_{\text{average,magnetic}}$$

- 谐振网络Q值@ ω_0

$$Q_L = 2\pi \frac{E_{\text{average,magnetic}} + E_{\text{average,electric}}}{E_{\text{loss in one oscillation cycle}}}$$

$$E_{\text{peak,electric}} = \frac{C_p V_P^2}{2} = 2E_{\text{average,electric}}$$

$$E_{\text{loss in one oscillation cycle}} = \frac{2\pi}{\omega}\cdot\frac{V_P^2}{2R_p}$$

$$= 2\pi \frac{E_{\text{peak,magnetic}}}{E_{\text{loss in one oscillation cycle}}} = \frac{R_p}{\omega_0 L_p}$$

$$\omega_0 = \frac{1}{\sqrt{L_p C_p}}$$

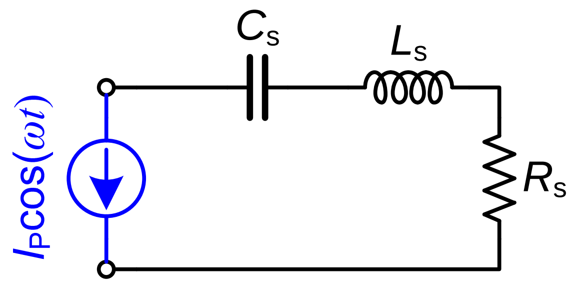
$$= 2\pi \frac{E_{\text{peak,electric}}}{E_{\text{loss in one oscillation cycle}}} = \omega_0 C_p R_p = \frac{R_p}{\sqrt{L_p / C_p}}$$

RLC串联谐振网络品质因数

- 电容Q值

$$Q_L = 2\pi \frac{E_{\text{peak,electric}} - E_{\text{peak,magnetic}}}{E_{\text{loss in one oscillation cycle}}} = 2\pi \frac{\dfrac{I_P{}^2}{2\omega^2 C_s} - \dfrac{I_P^2 L_s}{2}}{\dfrac{2\pi}{\omega}\cdot\dfrac{I_P^2 R_s}{2}}$$

$$= \frac{\omega L_s}{R_s}\left[\left(\frac{\omega_0}{\omega}\right)^2 - 1\right] = \frac{1}{\omega C_s R_s}\left[1 - \left(\frac{\omega}{\omega_0}\right)^2\right]$$



$$E_{\text{peak,magnetic}} = \frac{I_{\text{peak}}^2 L_s}{2} = \frac{I_P^2 L_s}{2} = 2E_{\text{average,magnetic}}$$

$$E_{\text{peak,electric}} = \frac{C_s V_{\text{peak}}{}^2}{2} = \frac{I_P{}^2}{2\omega^2 C_s} = 2E_{\text{average,electric}}$$

$$E_{\text{loss in one oscillation cycle}} = \frac{2\pi}{\omega}\cdot\frac{I_P^2 R_s}{2}$$

$$\omega_0 = \frac{1}{\sqrt{L_s C_s}}$$

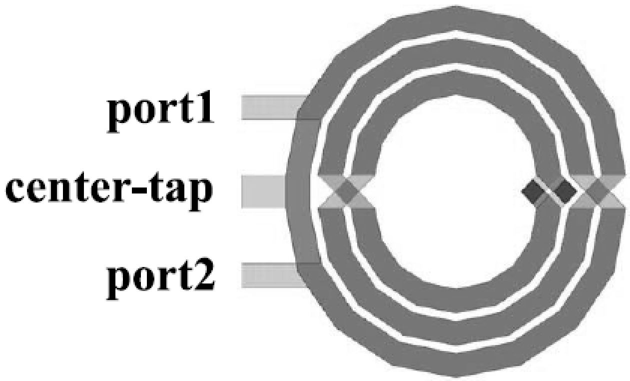
- 谐振网络Q值@ ω_0

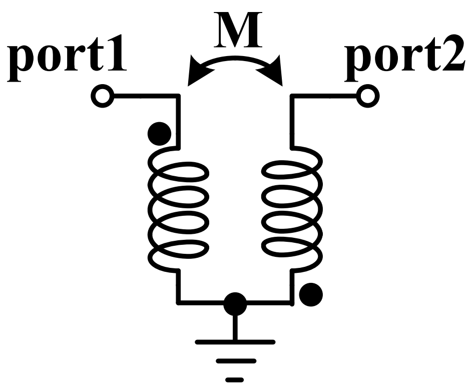
$$Q_L = 2\pi \frac{E_{\text{average,magnetic}} + E_{\text{average,electric}}}{E_{\text{loss in one oscillation cycle}}}$$

$$= 2\pi \frac{E_{\text{peak,magnetic}}}{E_{\text{loss in one oscillation cycle}}} = \frac{\omega_0 L_s}{R_s}$$

$$= 2\pi \frac{E_{\text{peak,electric}}}{E_{\text{loss in one oscillation cycle}}} = \frac{1}{\omega_0 C_s R_s} = \frac{\sqrt{L_s / C_s}}{R_s}$$

中心抽头差分电感





- 中心抽头差分电感应用场合
  - ❑采用中心抽头差分电感的压控振荡器的谐振网络
  - ❑用于正交压控振荡器中的源极二次谐波耦合
  - ❑全差分低噪声放大器和混频器的负载谐振网络

单端口S参数测量

- 单端口S参数测量

$$Z_{in}=Z_0\left(\frac{1+S_{11}}{1-S_{11}}\right)$$

❑端口2开路

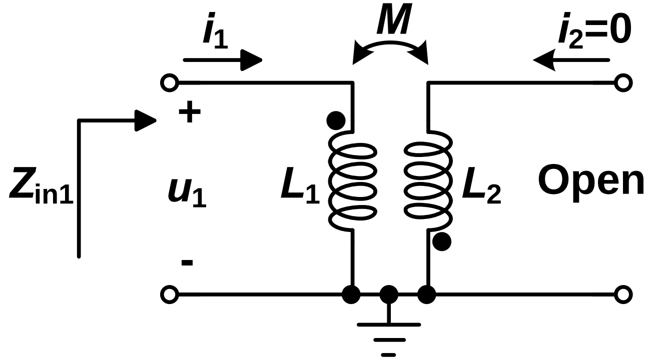
$$Z_{in}=j\omega L_1$$

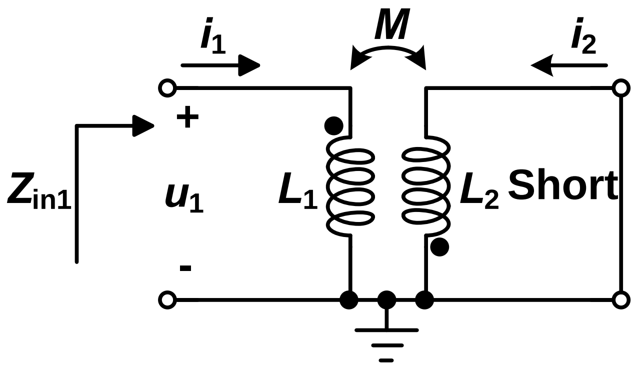
❑端口2短路

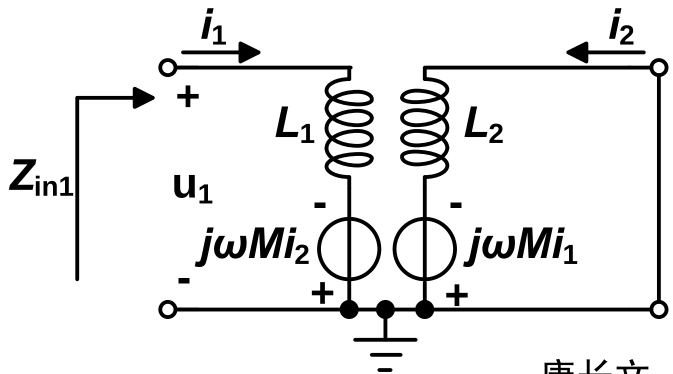
$$j\omega L_1 i_1-j\omega M i_2=u_1$$
$$-j\omega M i_1+j\omega L_2 i_2=0$$

$$L_1=L_2=L$$

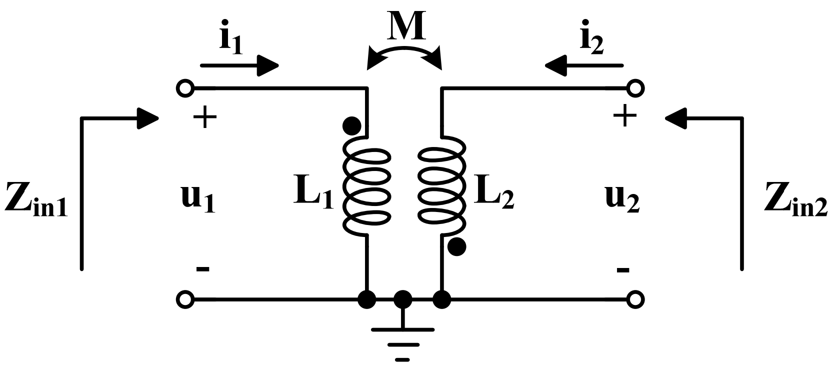
$$Z_{in1}=\frac{u_1}{i_1}=j\omega L\left(1-\frac{M^2}{L^2}\right)=j\omega L\left(1-k^2\right)$$

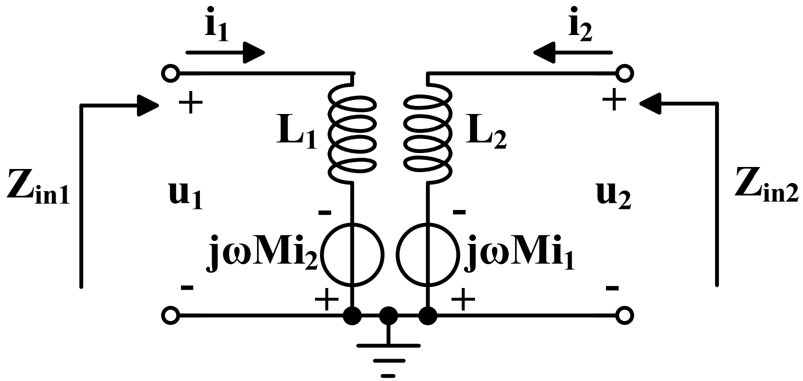






宽带180°相移网络的双端口S参数测量





$$j\omega L_1 i_1 - j\omega M i_2 = u_1 \qquad L_1 = L_2 = L$$

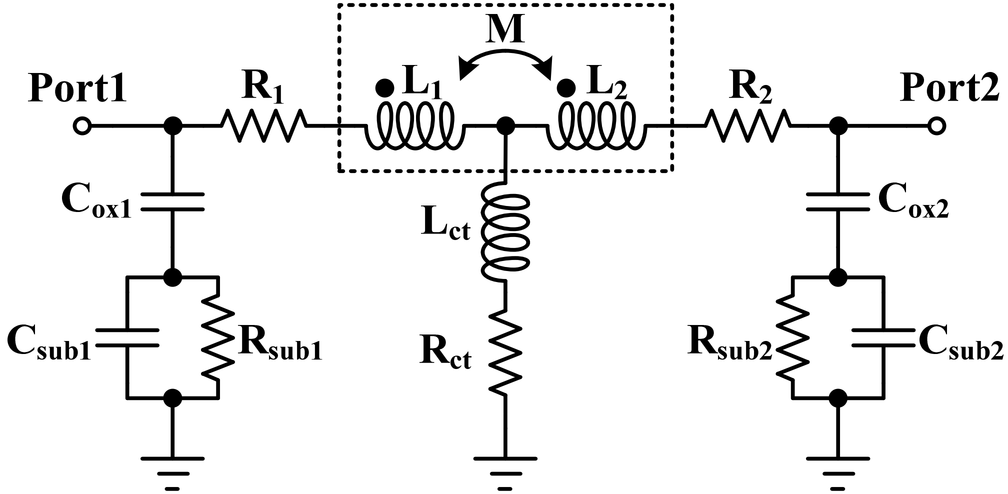
$$-j\omega M i_1 + j\omega L_2 i_2 = u_2 \qquad u_2 = -u_1$$

$$Z_{in1} = \frac{u_1}{i_1} = j\omega L\left(1+k\right) = j\omega\left(L+M\right)$$

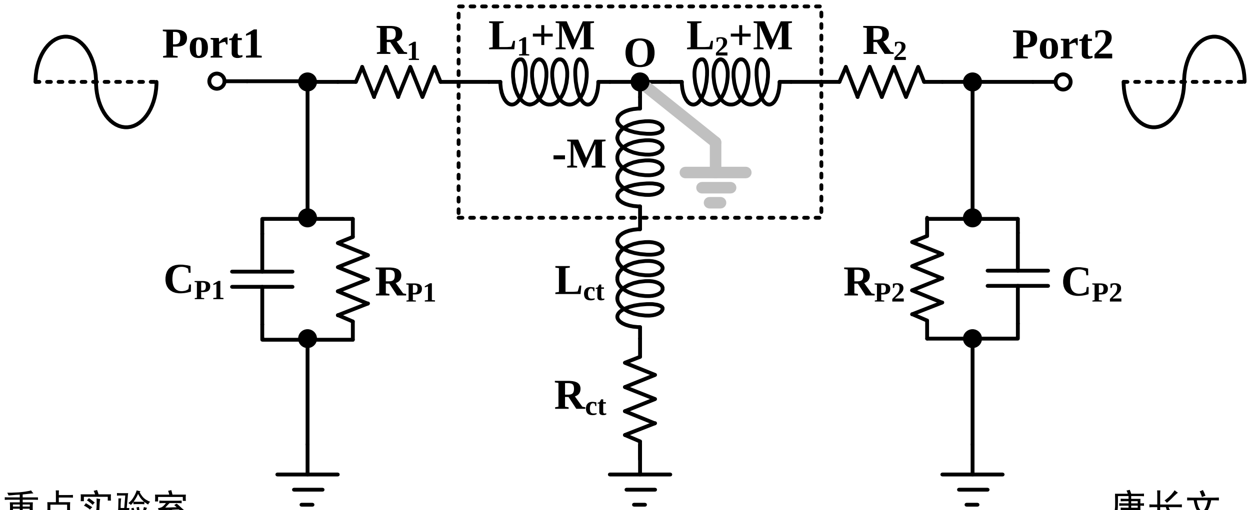
$$Z_{in2} = \frac{u_2}{i_2} = j\omega L\left(1+k\right) = j\omega\left(L+M\right)$$

中心抽头等效模型

- 集总电路模型

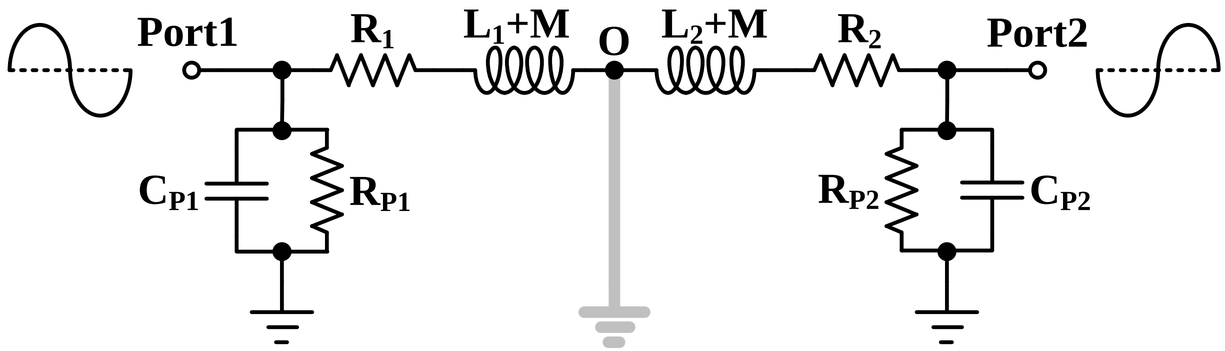


- 去耦等效集总电路模型

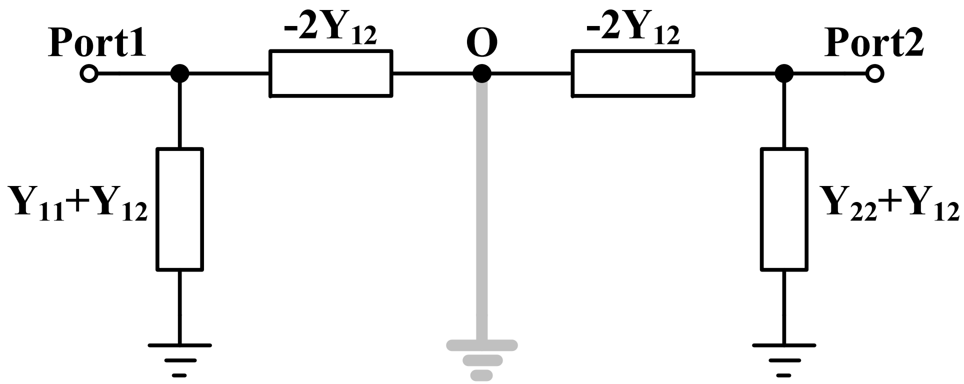


差分激励等效模型

- 差分激励的交流等效模型



- 中心抽头等效模型



差分激励单端阻抗和差分阻抗

- 单端阻抗

$$R_{se} + jX_{se} = \frac{1}{Y_{11} - Y_{12}}$$

- 差分阻抗

$$R_{diff} + jX_{diff} = \left(-\frac{1}{Y_{12}}\right) \Bigg\| \left(\frac{1}{Y_{11}+Y_{12}} + \frac{1}{Y_{22}+Y_{12}}\right) = \frac{Y_{11}+Y_{22}+2Y_{12}}{Y_{11}Y_{22}-Y_{12}^2}$$

$$= \frac{2}{Y_{11}-Y_{12}} \quad (Y_{11} = Y_{22})$$

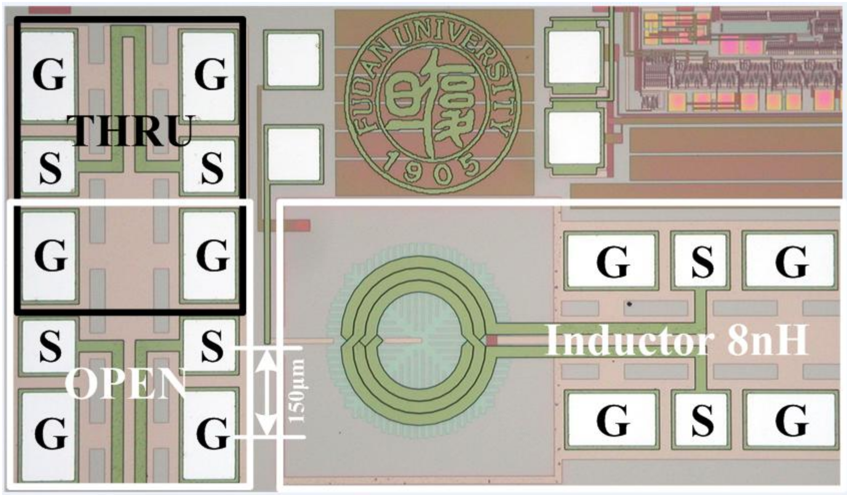
- ***RLQ*参数提取**

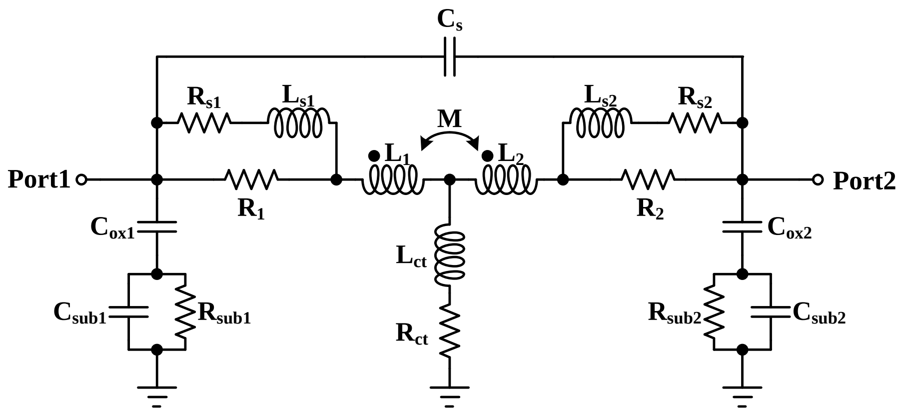
$$R_{eff} = \mathrm{Re}[R + jX] \qquad L_{eff} = \frac{\mathrm{Im}[R+jX]}{2\pi f}$$

$$Q_{eff} = \frac{\mathrm{Im}[R+jX]}{\mathrm{Re}[R+jX]} = \frac{2\pi f \cdot L_{eff}}{R_{eff}}$$

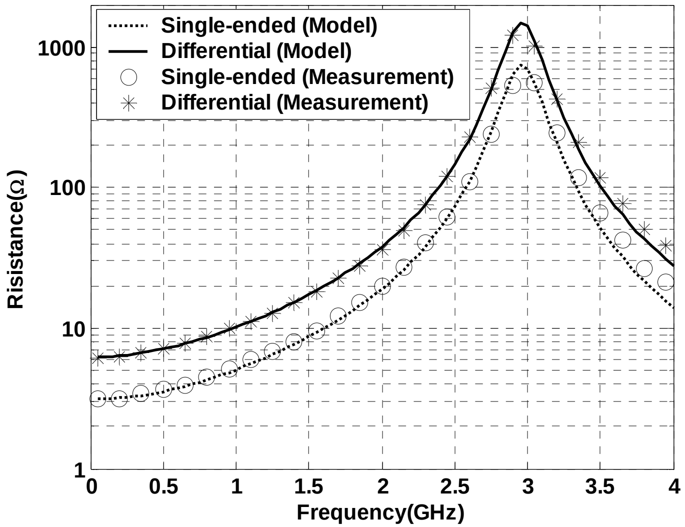
中心抽头等效模型的验证

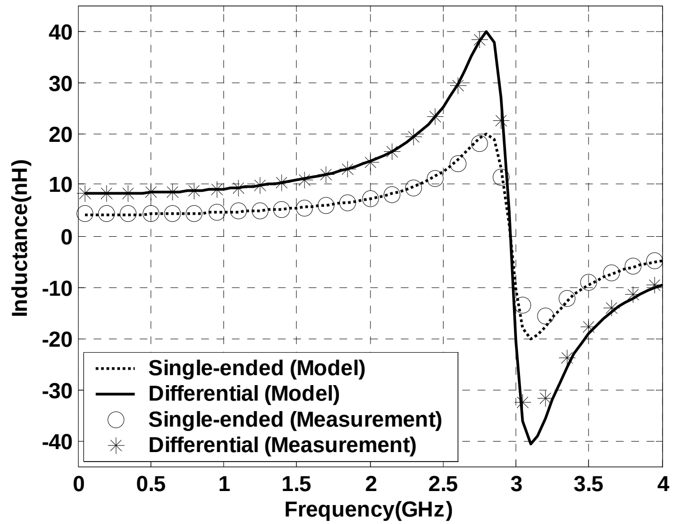
- **0.35 um 1P4M RF Mixed-signal Process**
- 第一、二层金属的并联再与第三、四层金属的并联相串联
- **M1**, **M2**和**M3**厚度为**0.64 um**，**M4**厚度为**0.895 um**

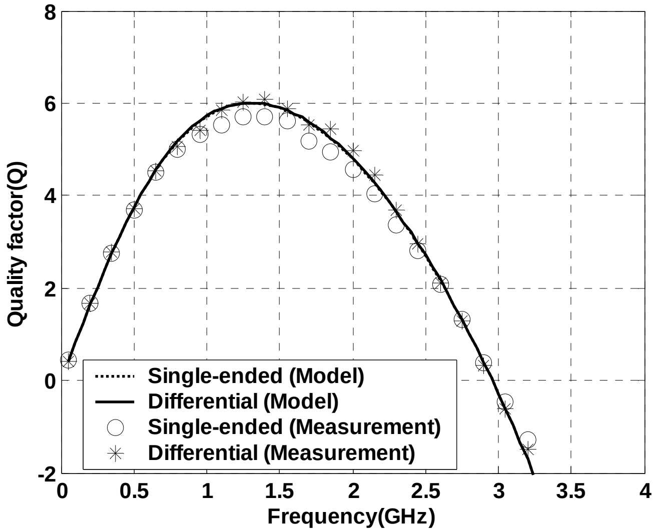


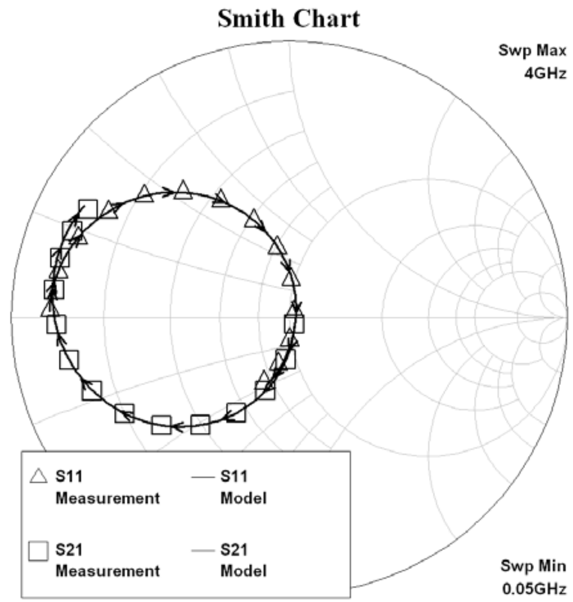


等效模型与测试结果的比较









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