电子电路与系统基础I

理论课第十二讲 晶体管放大器

负反馈与三种组态

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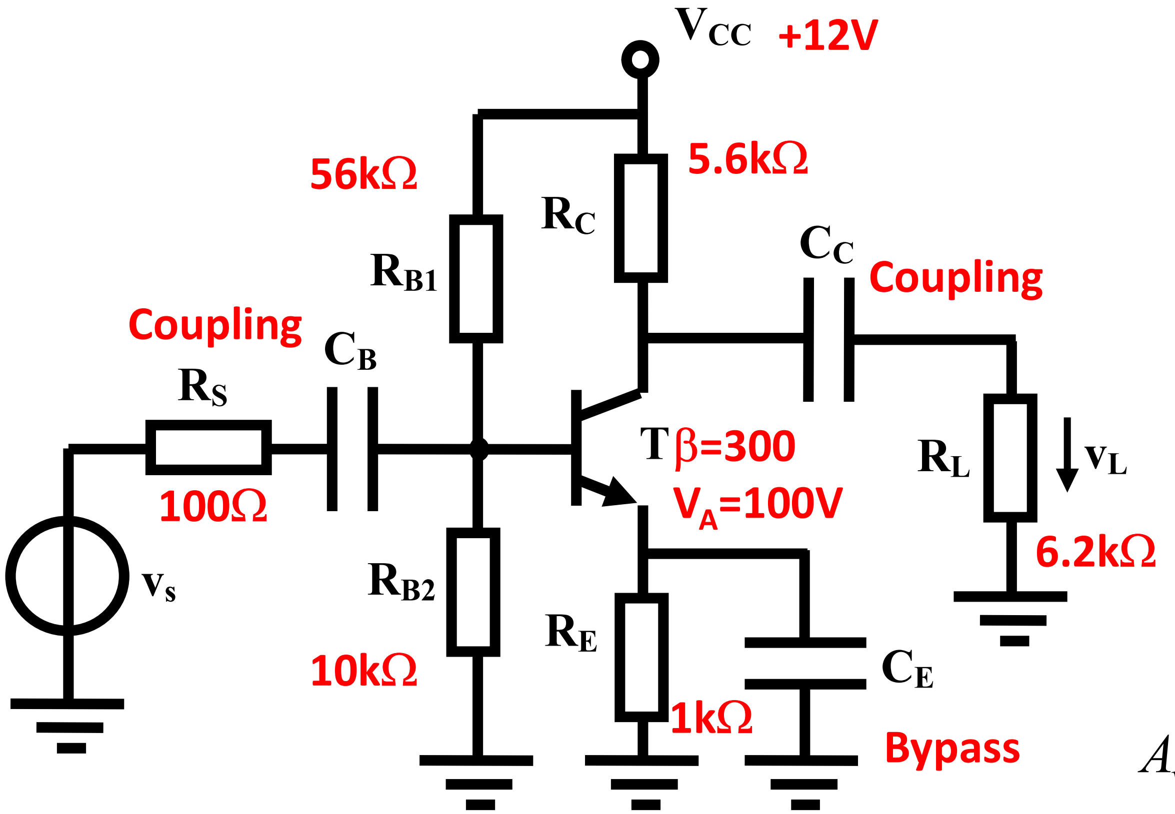
晶体管放大器　大纲

- 负反馈分析
  - **CE**组态放大器分析
    - 负反馈放大器的一般分析方法
  - 深度负反馈的实现
    - 高增益放大器

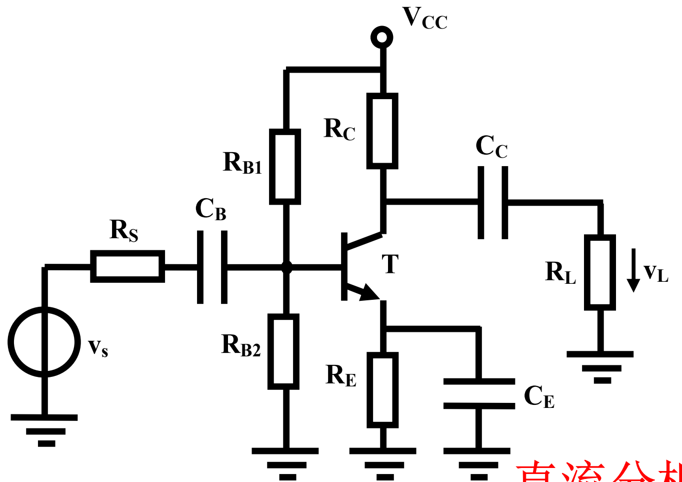
- 恒流区工作的晶体管的三种组态
  - **CE**、**CB**、**CC**组态特性及其简化等效电路
  - **CB**组态：放大器分析例
  - **CC**组态：电压缓冲器例

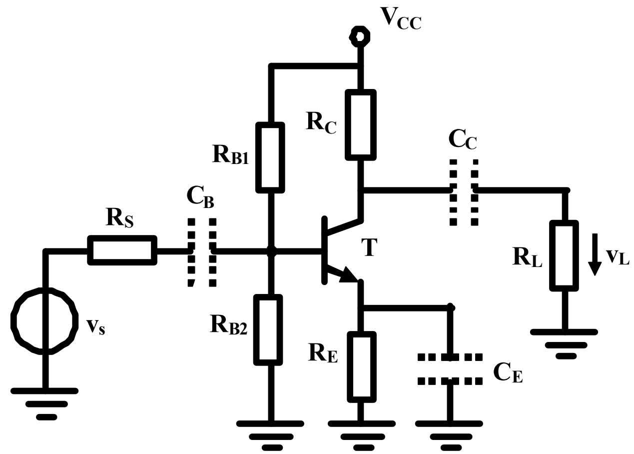
例3 NPN-BJT-CE放大器（续）



$$A_v = \frac{v_L}{v_S} = ?$$

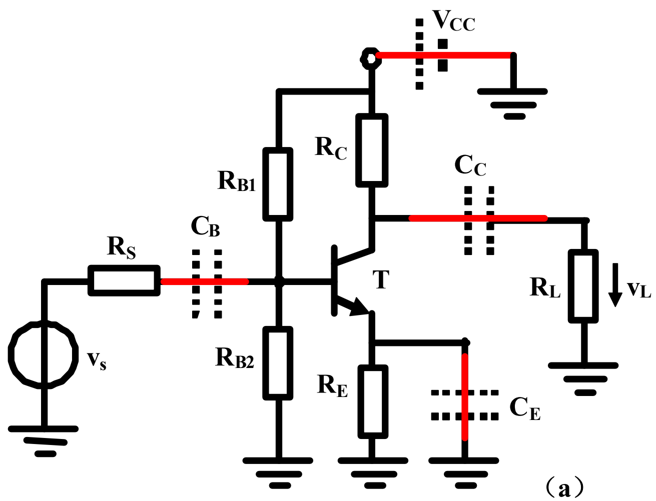
直流分析和交流分析





直流分析：获得直流工作点

分段折线法



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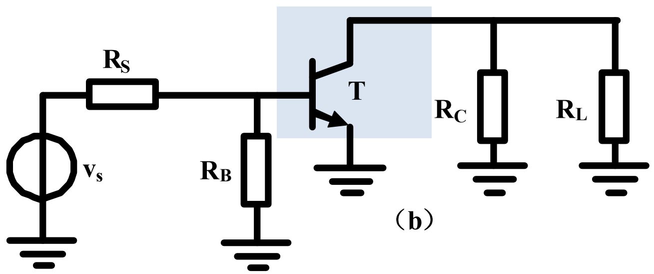
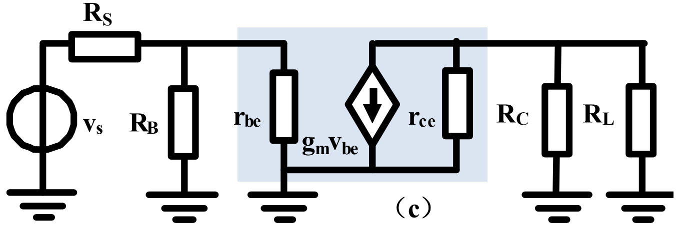


（b）



（c）

交流小信号分析：获得交流小信号电压放大倍数

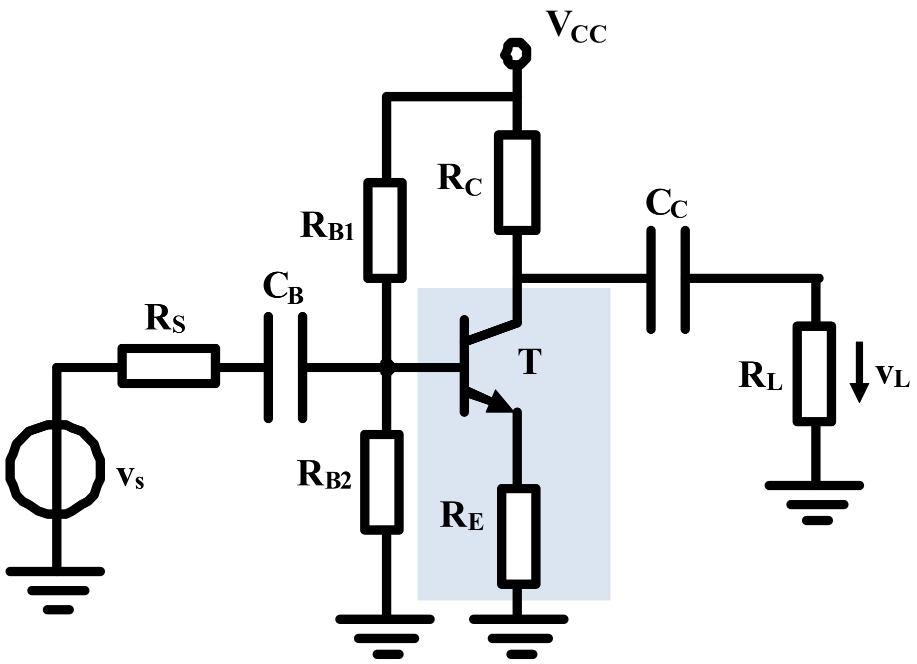
局部线性化：线性电路分析

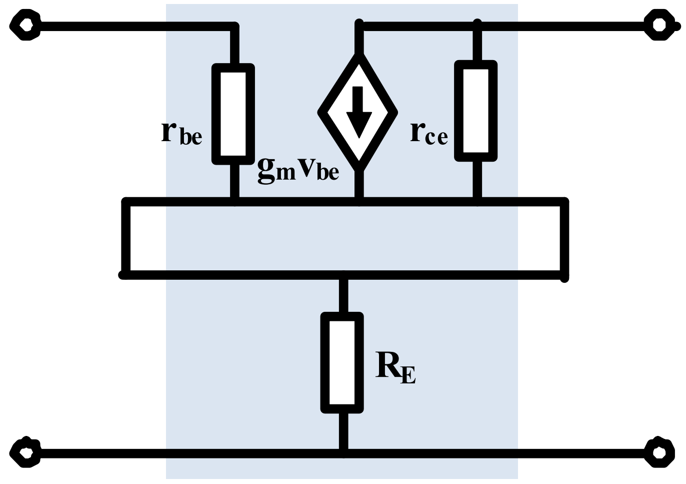
$$A_v = \frac{v_L}{v_S} = -115$$

41.2dB反相放大

如果没有旁路电容

发射极不是交流地：存在负反馈





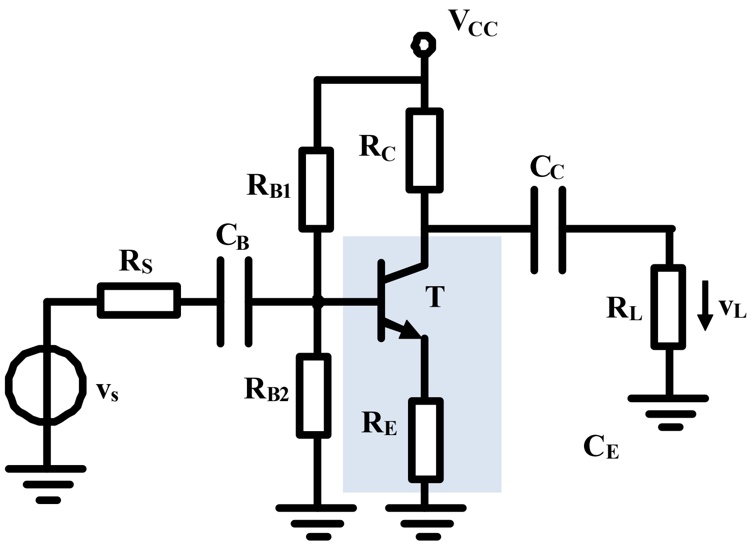
直流分析无影响

交流小信号分析

T和R_E构成的二端口网络

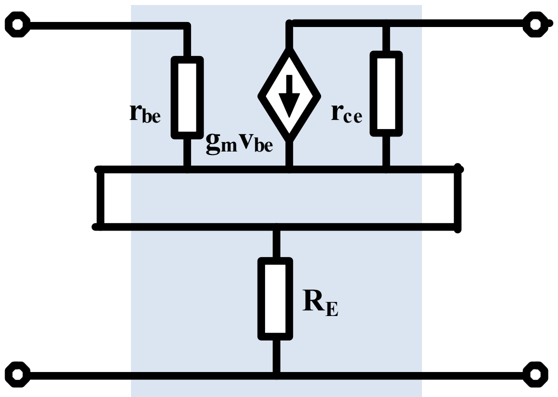
是T和R_E的串串连接关系

串串连接z相加数学操作



$$\mathbf{z}_T = \mathbf{y}_T^{-1} = \begin{bmatrix} g_{be} & 0 \\ g_m & g_{ce} \end{bmatrix}^{-1} = \begin{bmatrix} r_{be} & 0 \\ -g_m r_{be} r_{ce} & r_{ce} \end{bmatrix}$$

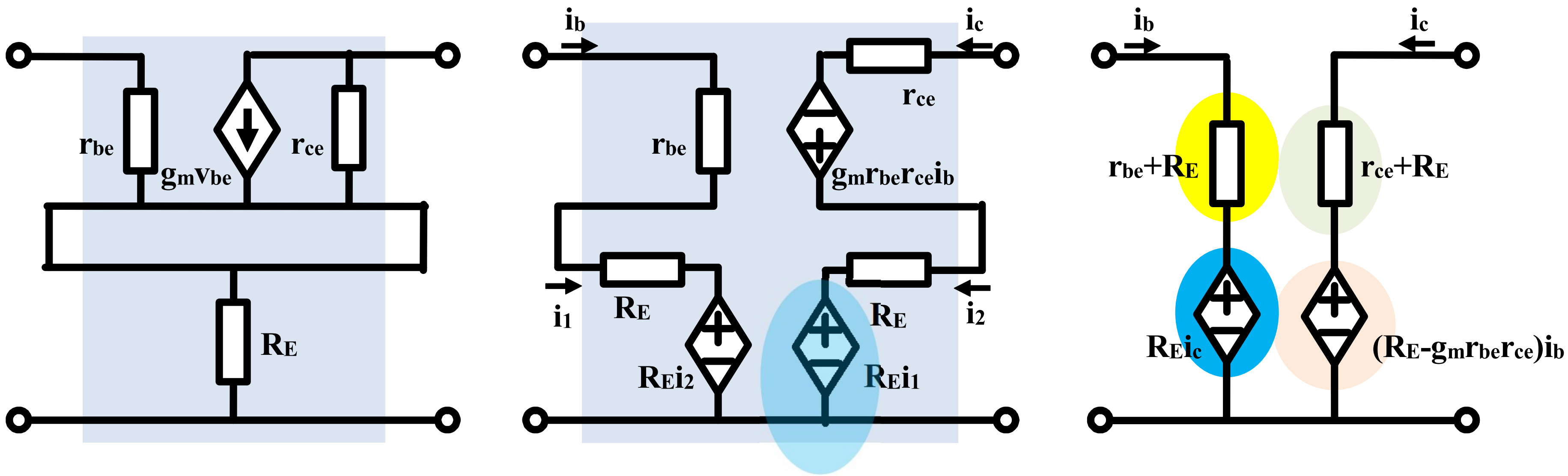
$$\mathbf{z}_E = \begin{bmatrix} R_E & R_E \\ R_E & R_E \end{bmatrix}$$



$$\mathbf{z} = \mathbf{z}_T + \mathbf{z}_E = \begin{bmatrix} r_{be} & 0 \\ -g_m r_{be} r_{ce} & r_{ce} \end{bmatrix} + \begin{bmatrix} R_E & R_E \\ R_E & R_E \end{bmatrix}$$

$$= \begin{bmatrix} r_{be} + R_E & R_E \\ -g_m r_{be} r_{ce} + R_E & r_{ce} + R_E \end{bmatrix}$$

串串连接z相加的电路操作



$$\mathbf{z} = \mathbf{z}_T + \mathbf{z}_E = \begin{bmatrix} r_{be} & 0 \\ -g_m r_{be} r_{ce} & r_{ce} \end{bmatrix} + \begin{bmatrix} R_E & R_E \\ R_E & R_E \end{bmatrix} = \begin{bmatrix} r_{be} + R_E & R_E \\ -g_m r_{be} r_{ce} + R_E & r_{ce} + R_E \end{bmatrix}$$

影响可以忽略不计

开环与闭环

输入端口负载效应　　反馈系数

$$\mathbf{z}=\mathbf{z}_T+\mathbf{z}_E=\begin{bmatrix} r_{be}+R_E & R_E \\ -g_m r_{be} r_{ce}+R_E & r_{ce}+R_E \end{bmatrix}=\begin{bmatrix} r_{in} & R_F \\ -G_{m0} r_{in} r_{out} & r_{out} \end{bmatrix}$$

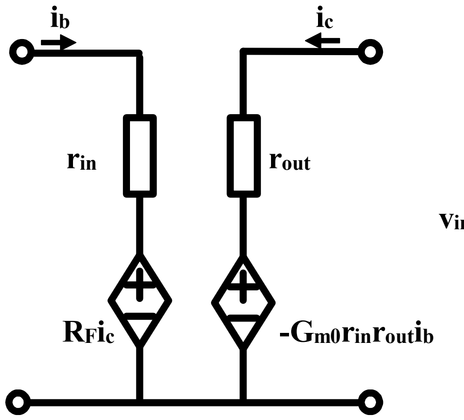
可能需要考虑输入端口负载效应　　影响可以忽略不计　　输出端口负载效应

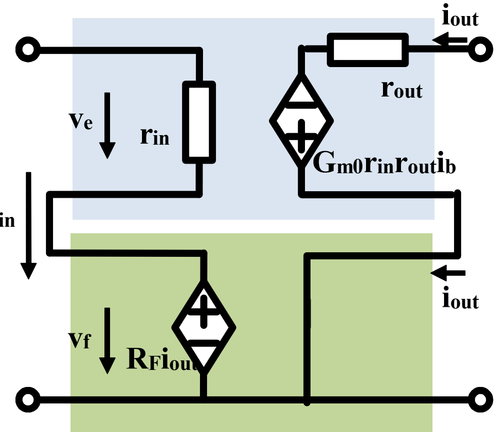
$$=\begin{bmatrix} r_{in} & 0 \\ -G_{m0} r_{in} r_{out} & r_{out} \end{bmatrix}+\begin{bmatrix} 0 & R_F \\ 0 & 0 \end{bmatrix}=\mathbf{z}_{Ao}+\mathbf{z}_F=\begin{bmatrix} g_{in} & 0 \\ G_{m0} & g_{out} \end{bmatrix}^{-1}+\begin{bmatrix} 0 & R_F \\ 0 & 0 \end{bmatrix}$$

一般无需考虑反馈网络的前向作用　　可能需要考虑输出端口负载效应　　反馈系数由反馈网络提供

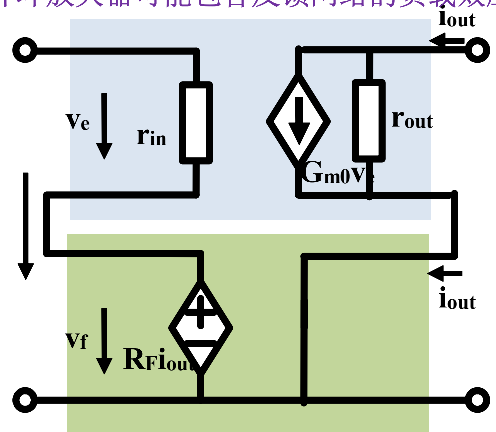
开环放大器单向网络　　理想反馈网络单向网络　　开环跨导放大器　　输出对输入的反向作用即反馈

消除输出对输入的反馈即开环：但反馈网络的阻抗关系仍然保留称之为反馈网络的负载效应





开环放大器可能包含反馈网络的负载效应



而反馈系数纯由反馈网络提供

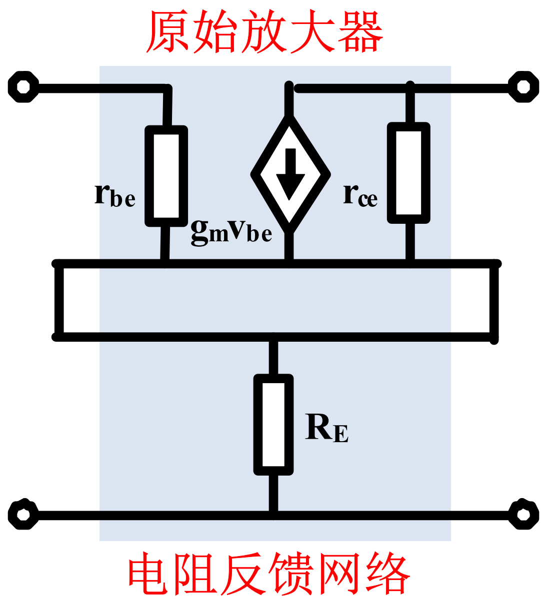
串串负反馈连接

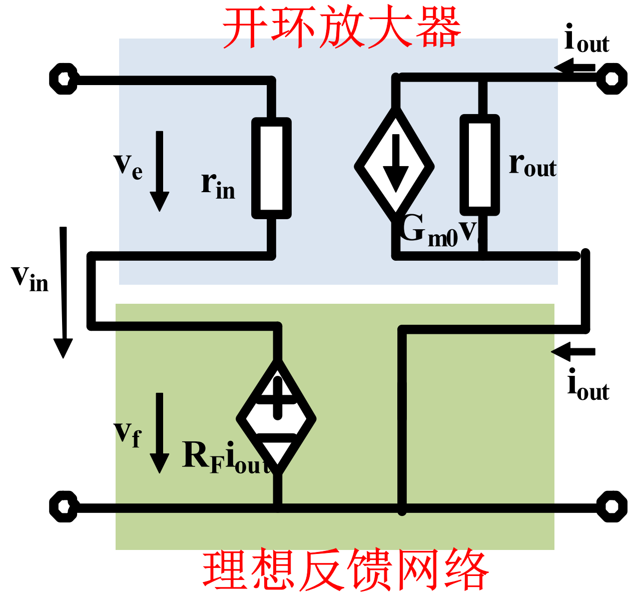
检测输出电流，形成反馈电压

压控流源y最适宜

$$\mathbf{z} = \mathbf{z}_T + \mathbf{z}_E = \mathbf{z}_{\mathbf{Ao}} + \mathbf{z}_{\mathbf{F}}$$

$$\mathbf{y} = \mathbf{z}^{-1}$$





$$r_{in} = r_{be} + R_E$$

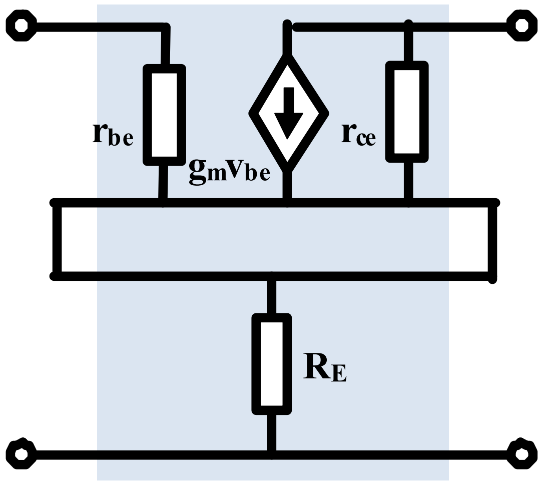
$$r_{out} = r_{ce} + R_E$$

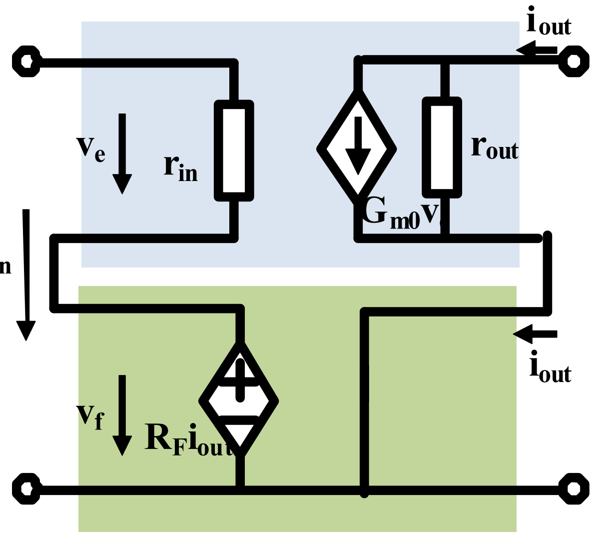
负载效应

$$G_{m0} = \frac{g_m r_{be} r_{ce} - R_E}{r_{in} r_{out}}$$

$$R_F = R_E$$

检测输出电流，形成反馈电压





$$r_{in} = r_{be} + R_E$$

$$r_{out} = r_{ce} + R_E$$

$$G_{m0} = \frac{g_m r_{be} r_{ce} - R_E}{r_{in} r_{out}}$$

$$R_F = R_E$$

压控流源 y 最适

$$\mathbf{z} = \mathbf{z}_{\mathbf{Ao}} + \mathbf{z}_{\mathbf{F}} = \begin{bmatrix} r_{in} & R_F \\ -G_{m0} r_{in} r_{out} & r_{out} \end{bmatrix}$$

$$\mathbf{y}_{OpenLoop} = \mathbf{z}_{OpenLoop}^{-1}$$

$$= \begin{bmatrix} r_{in} & 0 \\ -G_{m0} r_{in} r_{out} & r_{out} \end{bmatrix}^{-1}$$

$$= \begin{bmatrix} \frac{1}{r_{in}} & 0 \\ G_{m0} & \frac{1}{r_{out}} \end{bmatrix}$$

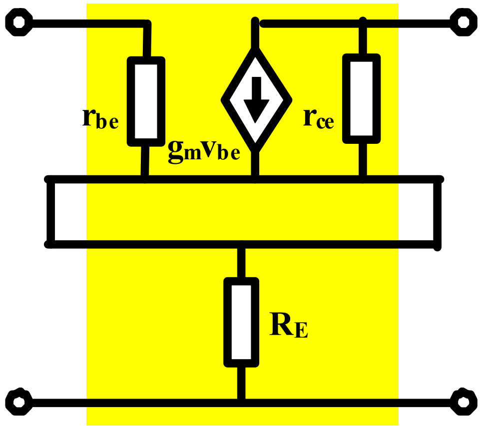
$$\mathbf{y} = \mathbf{z}^{-1} = \frac{1}{1 + G_{m0} R_F} \begin{bmatrix} \frac{1}{r_{in}} & \frac{-R_F}{r_{in} r_{out}} \\ G_{m0} & \frac{1}{r_{out}} \end{bmatrix}$$

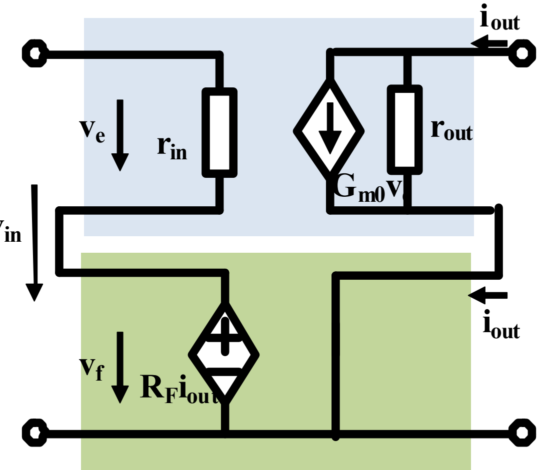
$$\overset{\text{满足单向化条件}}{\approx} \frac{1}{1 + G_{m0} R_F} \mathbf{y}_{OpenLoop}$$

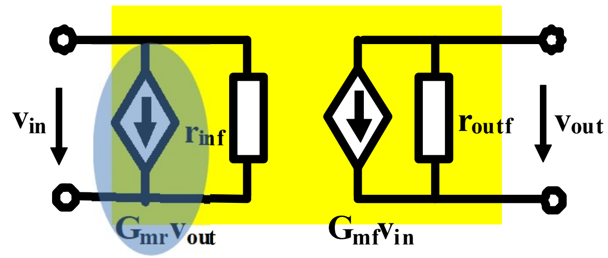
这就是为什么分析开环放大器的原因：避免数学过程

闭环放大器

$$\mathbf{z}=\begin{bmatrix} r_{in} & R_F \\ -G_{m0}r_{in}r_{out} & r_{out} \end{bmatrix} \qquad \mathbf{y}=\mathbf{z}^{-1}=\begin{bmatrix} \dfrac{1}{r_{inf}} & G_{mr} \\ G_{mf} & \dfrac{1}{r_{outf}} \end{bmatrix}$$







$$r_{inf}=r_{in}\left(1+G_{m0}R_F\right)$$

$$r_{outf}=r_{out}\left(1+G_{m0}R_F\right)$$

$$G_{mf}=\frac{G_{m0}}{1+G_{m0}R_F}$$

$$G_{mr}=\frac{-R_F}{r_{in}r_{out}\left(1+G_{m0}R_F\right)}$$

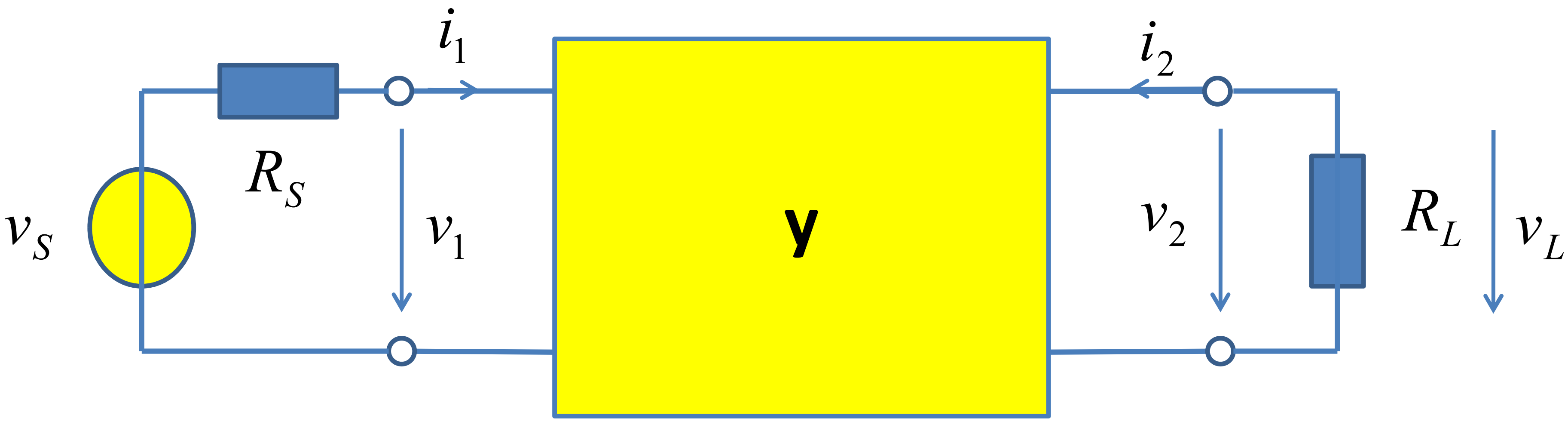
$$\mathbf{y}=\mathbf{z}^{-1}=\frac{1}{1+G_{m0}R_F}\begin{bmatrix} \dfrac{1}{r_{in}} & \dfrac{-R_F}{r_{in}r_{out}} \\ G_{m0} & \dfrac{1}{r_{out}} \end{bmatrix}$$

G_{mr}很小的数值，满足单向化条件则可忽略其影响

$$\left|G_{mr}G_{mf}\right| << \left|\left(\frac{1}{r_{inf}}+G_S\right)\left(\frac{1}{r_{outf}}+G_L\right)\right|$$

R_S和R_L不要过大即可视为单向放大网络

双向网络何时可视为单向网络？



$$H=\frac{v_L}{v_S}=\frac{y_{21}G_S}{y_{21}y_{12}-\left(y_{11}+G_S\right)\left(y_{22}+G_L\right)}\approx\frac{y_{21}G_S}{-\left(y_{11}+G_S\right)\left(y_{22}+G_L\right)}$$

双向网络传递函数　　　　单向网络传递函数

$$\left|y_{21}y_{12}\right|<<\left|\left(y_{11}+G_S\right)\left(y_{22}+G_L\right)\right|$$

单向化条件

$$|y_{21}y_{12}| << |(y_{11}+G_S)(y_{22}+G_L)|$$

见教材习题4.14分析

假设满足闭环单向化条件

$$R_S << r_{in} \text{或} R_L << r_{out} \text{或} \quad R_S R_L << \frac{r_{inf}r_{outf}}{G_{m0}R_F} \approx r_{in}r_{out}G_{m0}R_F$$

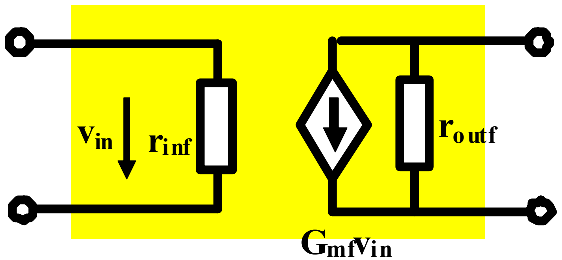
通常情况下，上述三个条件满足其一，则可单向化处理为单向跨导放大器

$$\mathbf{y} = \mathbf{z}^{-1} = \begin{bmatrix} \dfrac{1}{r_{in}(1+G_{m0}R_F)} & \dfrac{-R_F}{r_{in}r_{out}(1+G_{m0}R_F)} \\ \dfrac{G_{m0}}{1+G_{m0}R_F} & \dfrac{1}{r_{out}(1+G_{m0}R_F)} \end{bmatrix} \approx \begin{bmatrix} \dfrac{1}{r_{inf}} & 0 \\ G_{mf} & \dfrac{1}{r_{outf}} \end{bmatrix} = \frac{1}{1+G_{m0}R_F}\mathbf{y}_{OpenLoop}$$

$$r_{inf} = r_{in}(1+G_{m0}R_F)$$

$$r_{outf} = r_{out}(1+G_{m0}R_F)$$

$$G_{mf} = \frac{G_{m0}}{1+G_{m0}R_F} \approx \frac{1}{R_F}$$



这个结论使得我们在进行负反馈放大器分析时，只需分别分析获得反馈系数和开环放大器，即可获得闭环放大器的基本特性

深度负反馈条件：**T=G$_{m0}$R$_F$>>1**：负反馈放大器性能几乎由负反馈网络决定

数值计算

不稳定，不可靠

$$g_m = \frac{I_{C0}}{v_T} = \frac{1.08mA}{26mV} = 41.5mS$$

$$r_{be} = \beta\frac{1}{g_m} = 300\times 24\Omega = 7.22k\Omega$$

$$r_{ce} = \frac{V_A}{I_{C0}} = \frac{100V}{1.08mA} = 92.6k\Omega$$

$R_E = 1k\Omega$ 稳定，可靠

$$\mathbf{z} = \mathbf{z}_T + \mathbf{z}_E = \begin{bmatrix} r_{be}+R_E & R_E \\ -g_m r_{be} r_{ce} + R_E & r_{ce}+R_E \end{bmatrix} = \begin{bmatrix} 7.22+1 & 1 \\ -27778+1 & 92.6+1 \end{bmatrix} k\Omega = \begin{bmatrix} 8.22 & 1 \\ -27777 & 93.6 \end{bmatrix} k\Omega$$

$$\mathbf{y} = \mathbf{z}^{-1} = \begin{bmatrix} 3.28 & -0.0350 \\ 973 & 0.288 \end{bmatrix} \mu S \overset{???}{\approx} \begin{bmatrix} 3.28 & 0 \\ 973 & 0.288 \end{bmatrix} \mu S$$

是否可视为单向网络？

$R_S = 100\Omega << r_{in} = 8.22k\Omega$或

$R_L' = R_L \parallel R_C = 2.94k\Omega << r_{out} = 93.6k\Omega$或

$$R_S R_L' = 2.94\times 10^5 (\Omega)^2 << \frac{r_{inf} r_{outf}}{G_{m0} R_F} = \frac{1}{|y_{12} y_{21}|} = 2.93\times 10^{10} (\Omega)^2$$

视为单向网络毫无问题

也可以不走数学过程，直接给答案：

$$r_{inf} = \frac{1}{y_{11}} = 305k\Omega \approx r_{be}(1+g_m R_E) = 307k\Omega$$

大得可视为无穷：可靠

$$r_{outf} = \frac{1}{y_{22}} = 3.47M\Omega \approx r_{ce}(1+g_m R_E) = 3.94M\Omega$$

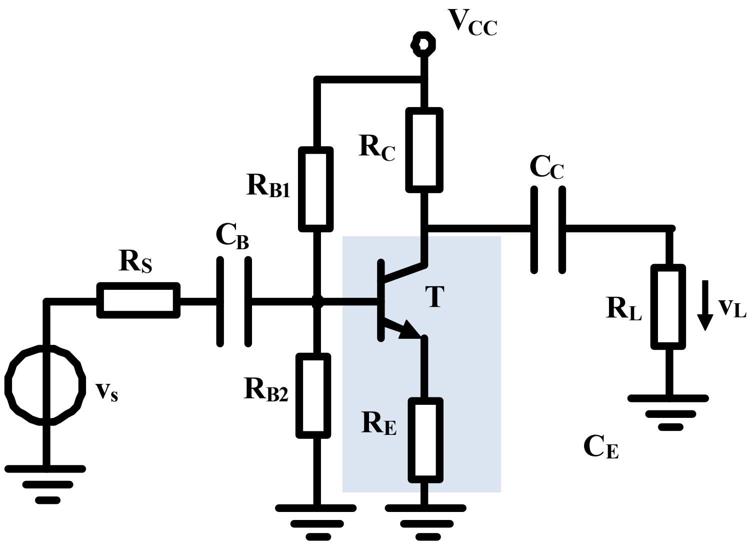
深度负反馈

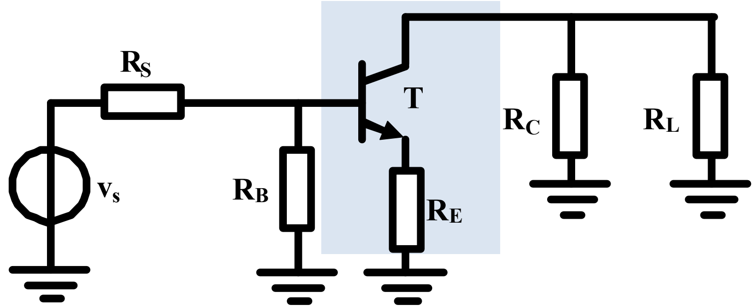
$$G_{mf} = 973\mu S \approx \frac{1}{R_F} = 1mS$$

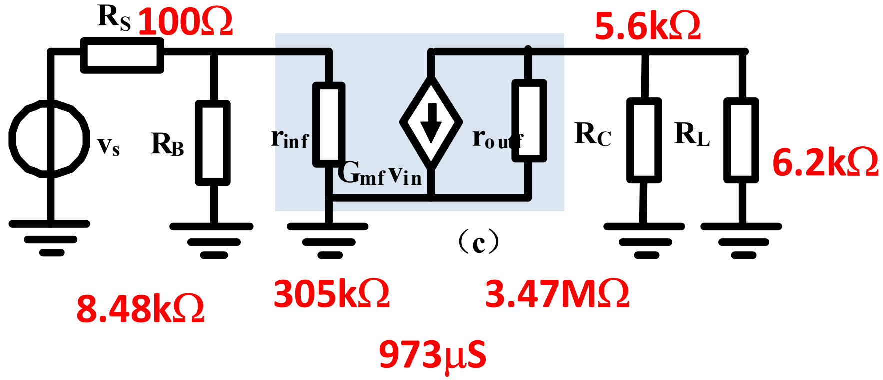
闭环增益几乎由反馈网络决定：可靠

没有旁路电容

电压增益太低







$$A_v \approx -G_{mf}R_L' = -973\mu S \times 2.94k\Omega = -2.86 \sim -\frac{R_L'}{R_E} = -2.94$$

无旁路电容

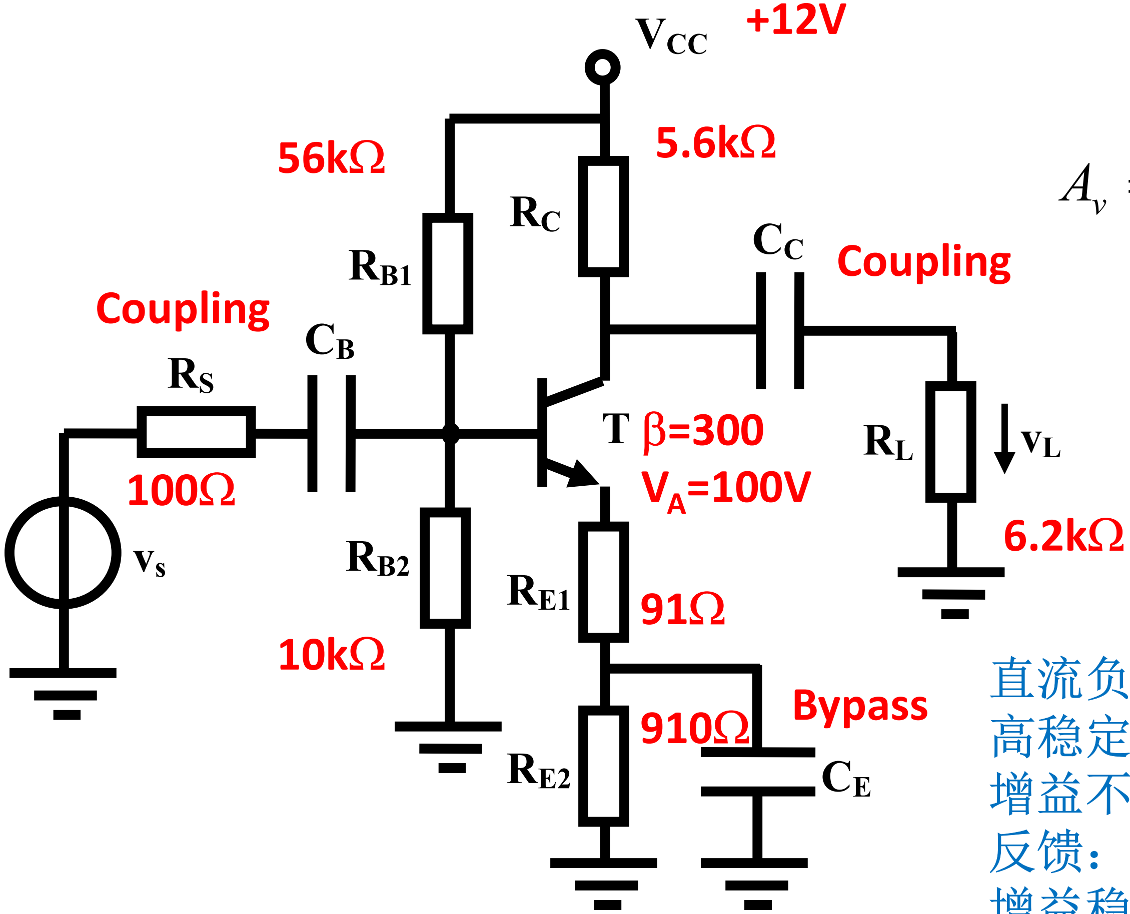
9dB的反相电压增益：不令人满意
但温度敏感度低：令人满意

有旁路电容

$$A_v = \frac{v_L}{v_S} = -115 \sim -g_m R_L' = -122$$

41dB的反相电压增益：令人满意
温度敏感度高：不令人满意

电路上的折中方案



反馈深度不够，
估算误差稍大

$$A_v = \frac{v_L}{v_S} = -25.5 \sim -\frac{R_L'}{R_{E1}} = -32.2$$

28dB　　30dB

电压增益下降伴随的好处：交流小信号增益稳定性提高

直流负反馈很深，确保直流工作点的高稳定性；交流负反馈较浅，使电压增益不致太低，同时提供串串交流负反馈：接近理想压控流源，提高电压增益稳定性，提高放大器带宽，提高线性度

负反馈的优点

$T = G_{m0}R_F, R_{m0}G_F, A_{v0}F_v, A_{i0}F_i$

环路增益 = 开环放大倍数 × 反馈系数

- 负反馈使得放大器接近理想受控源
  - 输入电阻、输出电阻变得更大或更小
    - 理想受控源输入电阻、输出电阻或无穷、或为零
    - 串联则阻抗变大，并联则阻抗变小

$$r_{inf} = r_{in}(1+T), \frac{r_{in}}{1+T}$$

$$r_{outf} = r_{out}(1+T), \frac{r_{out}}{1+T}$$

$$A_f = \frac{A_0}{1+A_0F} \overset{T=A_0F>>1}{\approx} \frac{1}{F}$$

$$G_{mf} = \frac{G_{m0}}{1+G_{m0}R_F} \overset{T=G_{m0}R_F>>1}{\approx} \frac{1}{R_F}$$

- 提高稳定性
- 提高线性度
- 提高带宽

负反馈使得增益不再由放大网络单独决定
深度负反馈增益几乎完全由反馈网络决定，等于反馈系数的倒数：反馈网络具有什么特性，闭环放大器则具有什么特性

实用的晶体管放大电路或多或少都存在着某种形式的负反馈结构

负反馈放大器拓展结论（1）

$$g_m = 41.5mS$$
$$r_{be} = 7.22k\Omega$$
$$r_{ce} = 92.6k\Omega$$
$$R_{E1} = 91\Omega$$

- 晶体管串联负反馈简单估算公式

$$\mathbf{z} = \mathbf{z}_T + \mathbf{z}_E = \begin{bmatrix} r_{be} + R_{E1} & R_{E1} \\ -g_m r_{be} r_{ce} + R_{E1} & r_{ce} + R_{E1} \end{bmatrix} = \begin{bmatrix} r_{in} & R_F \\ -G_{m0} r_{in} r_{out} & r_{out} \end{bmatrix}$$

$$r_{in} = r_{be} + R_{E1} \approx r_{be}$$

$$r_{out} = r_{ce} + R_{E1} \approx r_{ce}$$

$$G_{m0} = \frac{g_m r_{be} r_{ce} - R_{E1}}{r_{in} r_{out}} \approx g_m$$

$$R_F = R_{E1}$$

晶体管自身为跨导放大器，串串负反馈形成的是理想跨导器，两者一致：反馈网络负载效应可以忽略不计，开环放大器近似为原始放大器

$$T = G_{m0} R_F \approx g_m R_{E1} = 3.78$$ 反馈深度不深

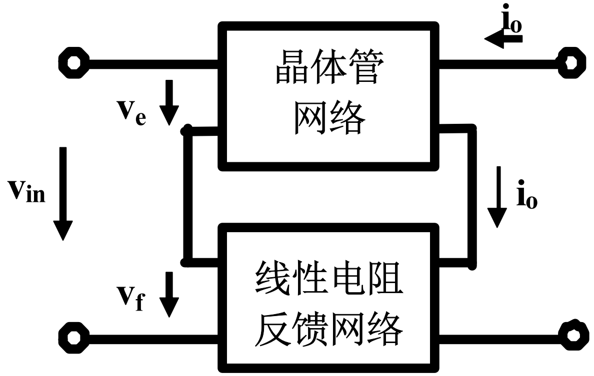
$$r_{inf} = r_{in}\left(1 + G_{m0} R_F\right) \approx r_{be}\left(1 + T\right) \approx 34.5k\Omega$$

$$r_{outf} = r_{out}\left(1 + G_{m0} R_F\right) \approx r_{ce}\left(1 + T\right) \approx 442k\Omega$$

$$G_{mf} = \frac{G_{m0}}{1 + G_{m0} R_F} \approx \frac{g_m}{1 + T} \approx 8.69mS$$

$$A_v = \frac{v_L}{v_S} \approx G_{mf} R_L' \approx 8.69m \times 2.94k = -25.5$$

负反馈放大器拓展研究（2）



串串负反馈

串串负反馈

（1）原理：检测输出电流i_o，形成反馈电压v_f，从输入信号v_{in}中扣除，形成误差电压v_e，作用到晶体管放大网络，稳定输出电流i_o。故而串串负反馈形成接近理想的压控流源

（2）分析：串串连接z相加，z_{12}元素为理想反馈网络的反馈系数R_F，扣除反馈系数作用后的单向放大网络称之为开环放大器，开环放大器输入电阻$r_{in}=z_{11}$，输出电阻$r_{out}=z_{22}$，开环跨导增益$G_{m0}=-z_{21}/(z_{11}z_{22})$。闭环放大器接近理想压控流源，其最适参量矩阵为y参量，故而对z求逆，$y=z^{-1}$。

（3）结果：闭环放大器环路增益$T=G_{m0}R_F$，输入电阻变大$r_{inf}=r_{in}(1+T)$，输出电阻变大$r_{outf}=r_{out}(1+T)$，闭环跨导增益$G_{mf}= G_{m0}/(1+T)$变得稳定了，在深度负反馈条件$T>>1$下，闭环跨导增益几乎是反馈系数的倒数

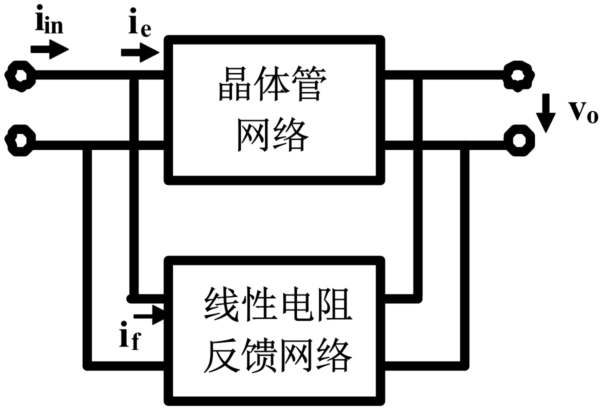
$$\mathbf{z}=\mathbf{z}_T+\mathbf{z}_E=\begin{bmatrix} r_{in} & R_F \\ -G_{m0}r_{in}r_{out} & r_{out}\end{bmatrix}$$

$$\mathbf{y}=\mathbf{z}^{-1}=\begin{bmatrix} \frac{1}{r_{in}(1+G_{m0}R_F)} & \frac{-R_F}{r_{in}r_{out}(1+G_{m0}R_F)} \\ \frac{G_{m0}}{1+G_{m0}R_F} & \frac{1}{r_{out}(1+G_{m0}R_F)}\end{bmatrix}$$

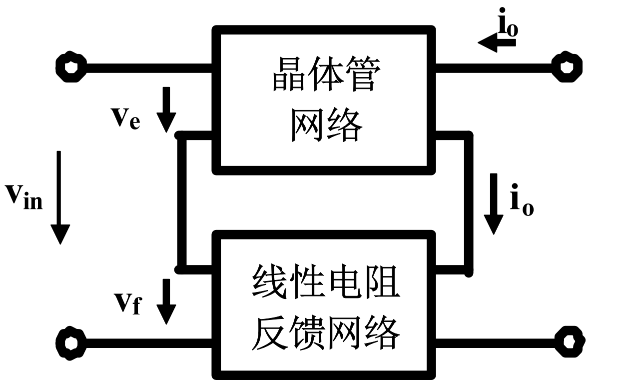
$$\overset{\text{单向化条件满足}}{\approx}\begin{bmatrix} \frac{1}{r_{inf}} & 0 \\ G_{mf} & \frac{1}{r_{outf}}\end{bmatrix}$$

$$G_{mf}=\frac{G_{m0}}{1+G_{m0}R_F}\overset{G_{m0}R_F>>1}{\approx}\frac{1}{R_F}$$

作业：三句话说清楚负反馈放大器

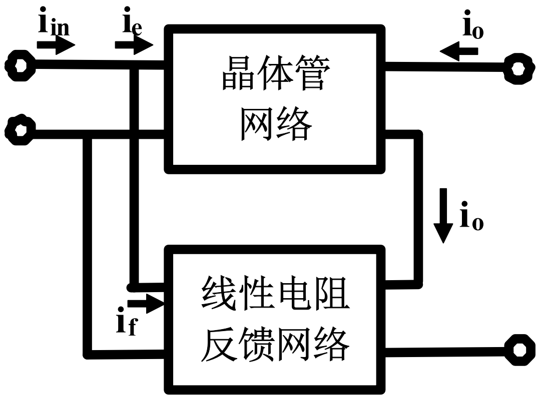


并并负反馈

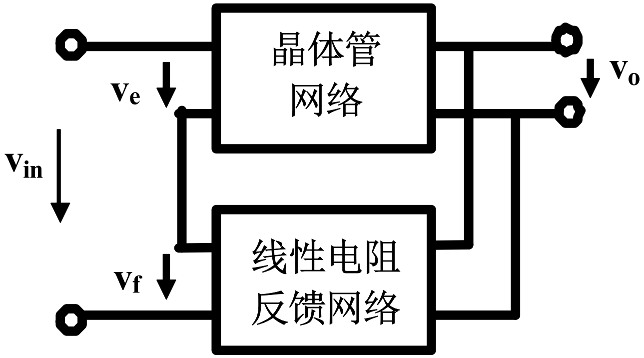


串串负反馈

仿照上页串串负反馈格式，用相同的语式描述所有**4**种负反馈放大器：**3**句话，**3**个公式



并串负反馈



串并负反馈

深度负反馈

$T = G_{m0}R_F, R_{m0}G_F, A_{v0}F_v, A_{i0}F_i$

环路增益 = 开环放大倍数 × 反馈系数

$T >> 1$

串串负反馈：$G_{m0}R_F >> 1$

并并负反馈：$R_{m0}G_F >> 1$

串并负反馈：$A_{v0}F_v >> 1$

并串负反馈：$A_{i0}F_i >> 1$

- 如何获得稳定的接近理想的受控源？
  - 深度负反馈
  - 首先获得高增益但增益不太确定的放大网络，之后用稳定的反馈网络，由于增益为反馈系数的倒数，故而闭环增益稳定
    - 开环高增益可以是任意一种增益，如运放高增益为高电压增益

串串负反馈：$G_{mf} = \dfrac{G_{m0}}{1 + G_{m0}R_F} \approx \dfrac{1}{R_F}$

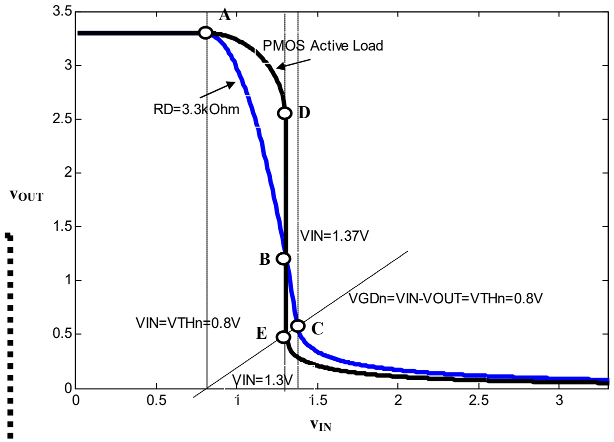
并并负反馈：$R_{mf} = \dfrac{R_{m0}}{1 + R_{m0}G_F} \approx \dfrac{1}{G_F}$

串并负反馈：$A_{vf} = \dfrac{A_{v0}}{1 + A_{v0}F_v} \approx \dfrac{1}{F_v}$

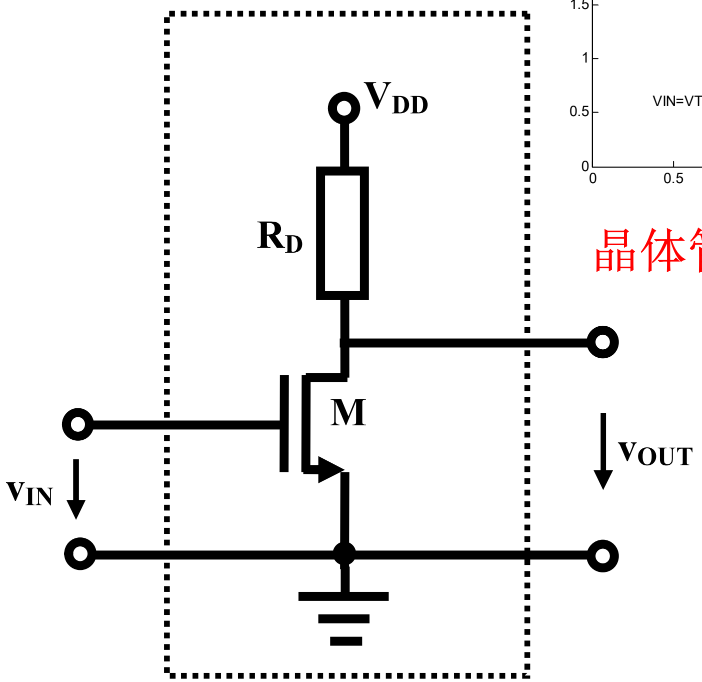
并串负反馈：$A_{if} = \dfrac{A_{i0}}{1 + A_{i0}F_i} \approx \dfrac{1}{F_i}$

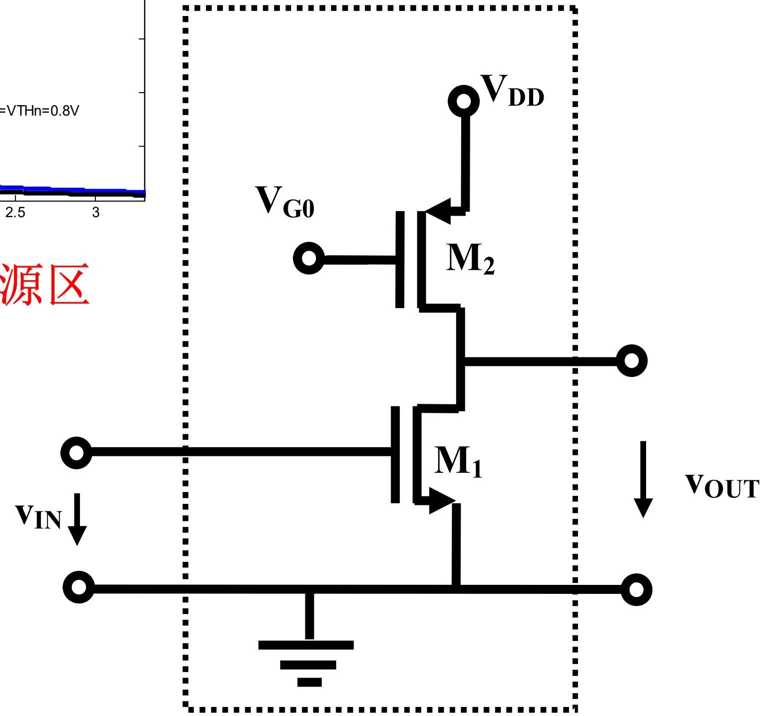
高增益放大器实现方案（1）

- 有源负载



晶体管都偏置在有源区

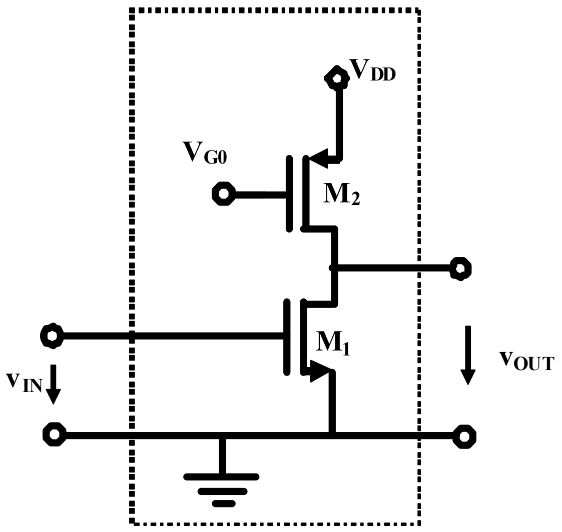


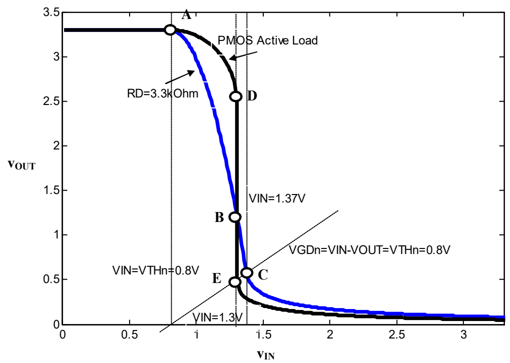


$$A_{v0} = -g_m\left(R_D \parallel r_{ds}\right) \approx -g_m R_D$$

$$A_{v0} = -g_m\left(r_{ds1} \parallel r_{ds2}\right)$$

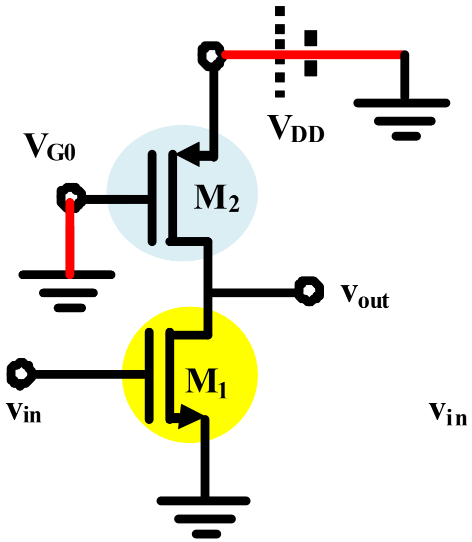
有源负载

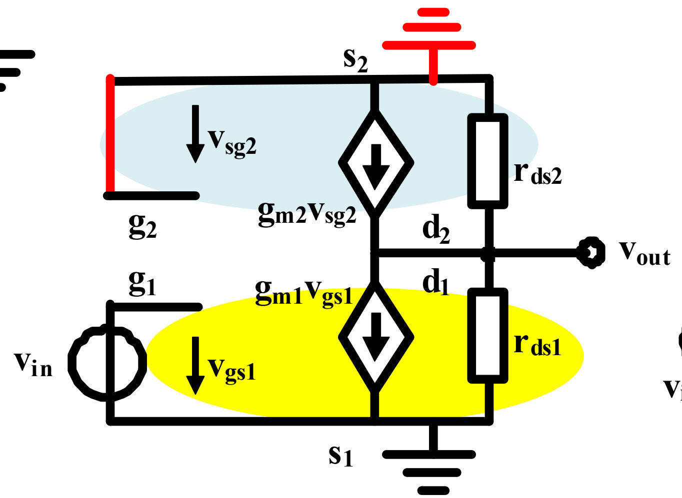




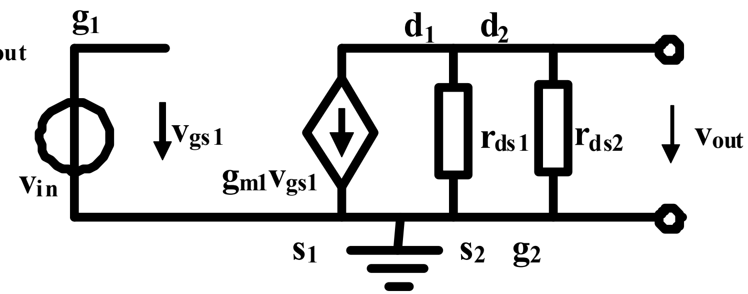
有源负载很大，可以获得高电压增益，但跨导器是受控电流源输出，驱动重负载（小电阻，需要大电流的称之为重）时，电压增益变小

交流小信号分析时，直流电压源都短接（恒压源微分电阻为0）





$$A_{v0} = -g_m \left(r_{ds1} \parallel r_{ds2} \right)$$

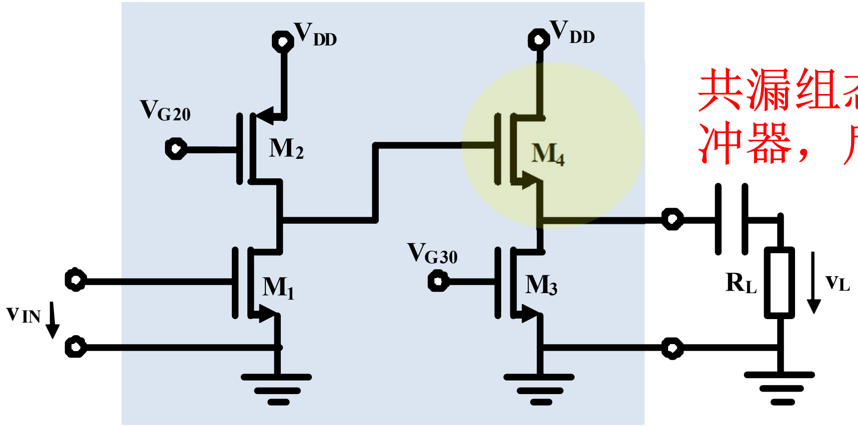


保留交流源，其他元件均用微分元件替代

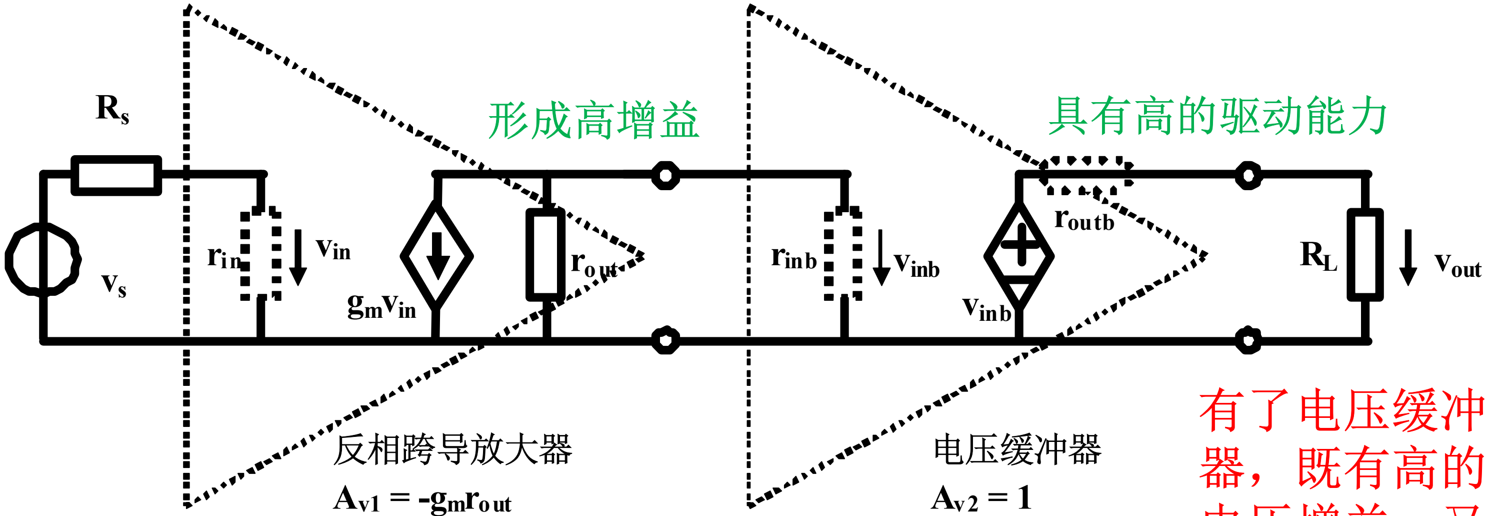
有源负载很大

高增益放大器实现方案（2）

- 缓冲器



共漏组态晶体管为电压缓冲器，后面马上给予确认

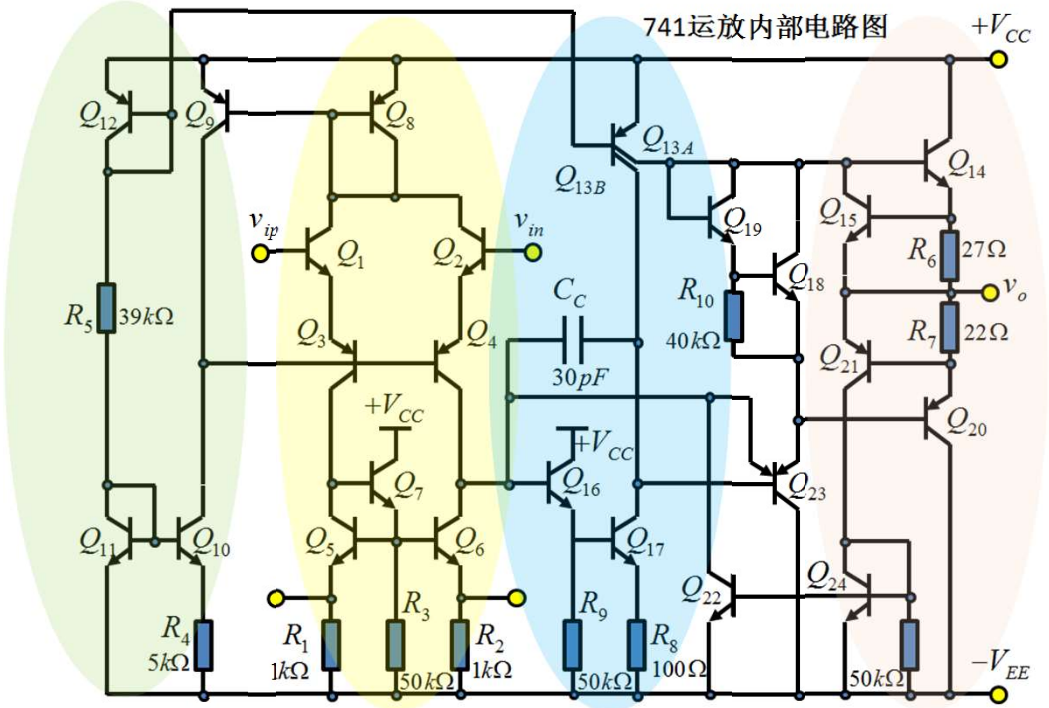


有了电压缓冲器，既有高的电压增益，又能驱动重负载

$$A_{v0} = A_{v1}A_{v2} = -g_m r_{out} \cdot 1 = -g_m \left(r_{ds1} \parallel r_{ds2}\right)$$

高增益放大器实现方案（3）

- 级联+缓冲



提供偏置的参考电流源

第一级
跨导放大器

第二级
跨导放大器

第三级
电压缓冲器

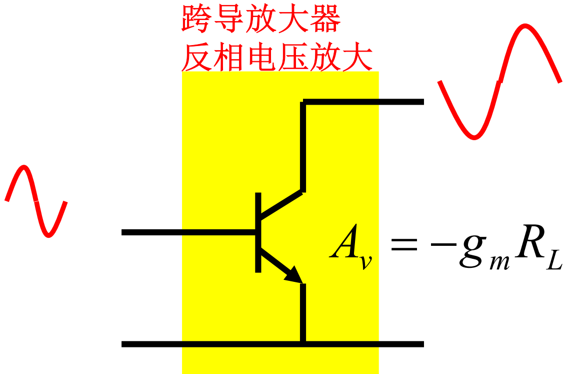
$$A_{v0} = A_{v1}A_{v2}A_{v3} = g_{m1}r_{out1}g_{m2}r_{out2} \sim 200000$$

$$r_{in} = r_{in1} \sim 2M\Omega$$

$$r_{out} = r_{out3} \sim 75\Omega$$

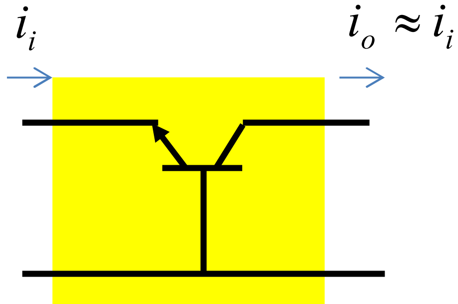
二、晶体管的三种组态

跨导放大器
反相电压放大



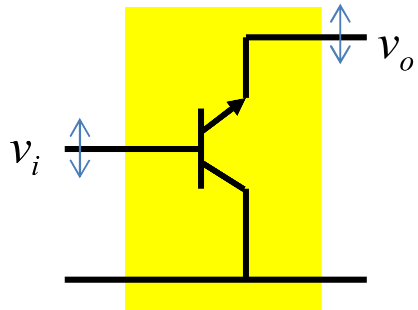
Common Emitter
CE：共射组态

电流缓冲器

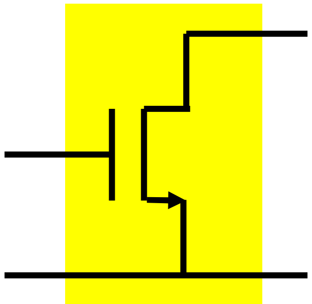


Common Base
CB：共基组态

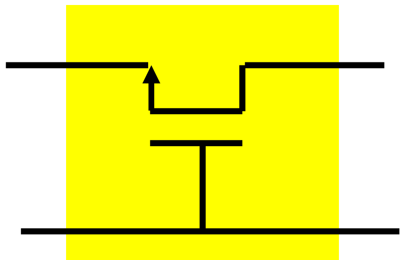
电压缓冲器



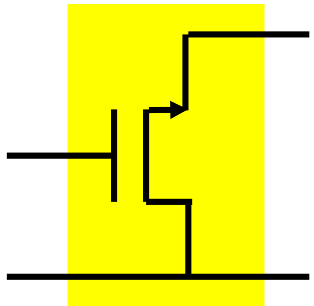
Common Collector
CC：共集组态



Common Source
CS：共源组态

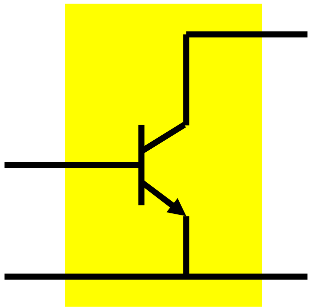


Common Gate
CG：共栅组态

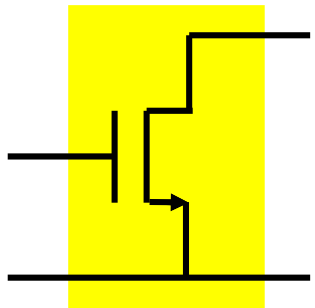


Common Drain
CD：共漏组态

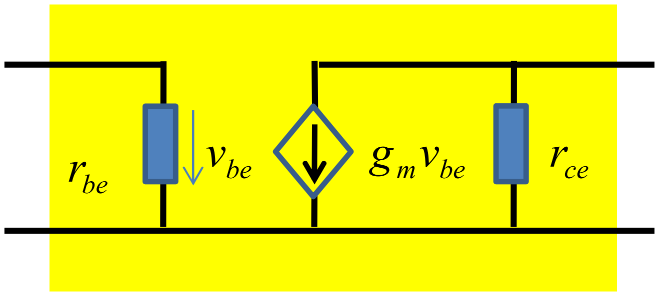
2.1 CE/CS组态
跨导放大器

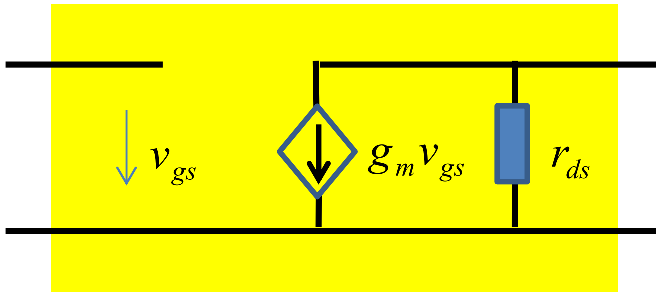


CE



CS





$$r_{in} = r_{be} = \beta \frac{v_T}{I_{C0}}$$

$$r_{out} = r_{ce} = \frac{V_A}{I_{C0}}$$

$$g_m = \frac{I_{C0}}{v_T}$$

$$Z_{01} = r_{be} \qquad Z_{02} = r_{ce}$$

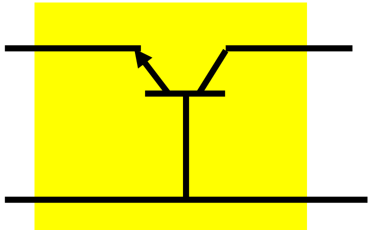
$$G_{pmax} = \frac{1}{\left(\sqrt{AD} + \sqrt{BC}\right)^2}$$

$$= \frac{1}{4AD} = \frac{1}{4} g_m^2 r_{be} r_{ce}$$

$$r_{in} \to \infty$$

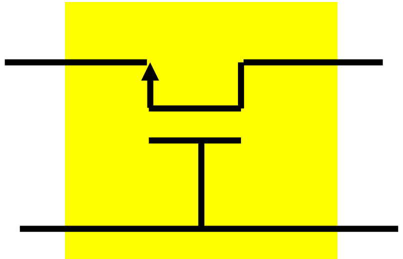
$$r_{out} = r_{ds} = \frac{V_E}{I_{D0}}$$

$$g_m = \frac{2I_{D0}}{V_{GS0} - V_{TH}} = \frac{2I_{D0}}{V_{od}}$$

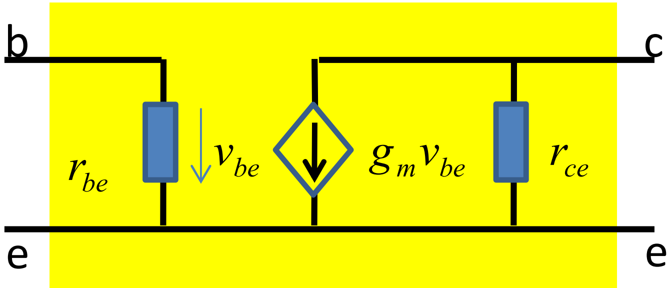


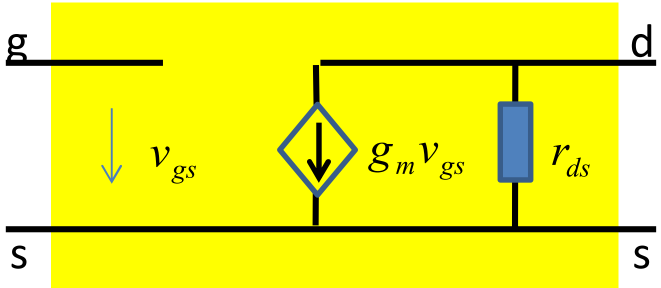
CB

2.2 CB/CG组态

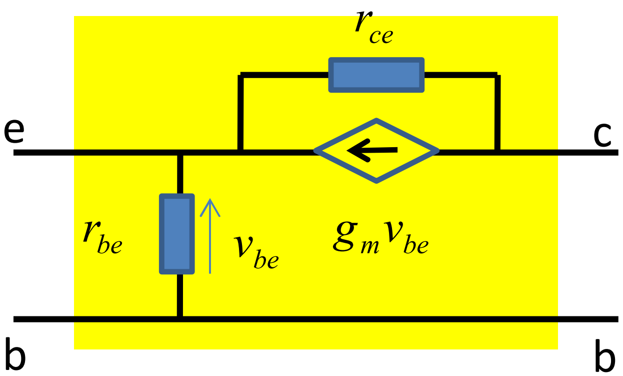


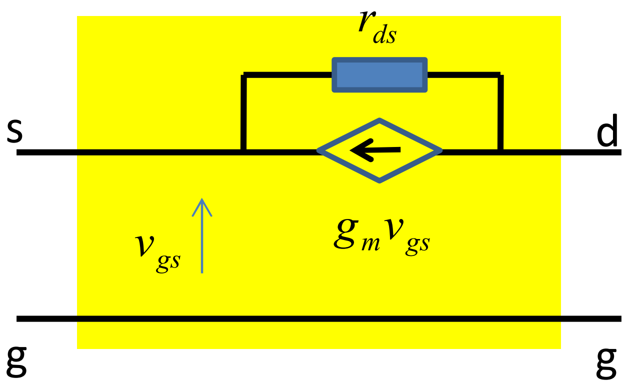
CG



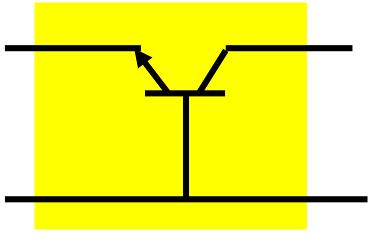


上节课建立交流小信号模型时，没有考虑任何组态问题，因而跨导器模型对任意组态都是可用的

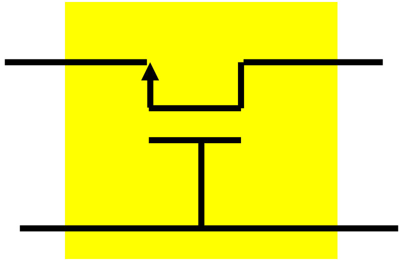




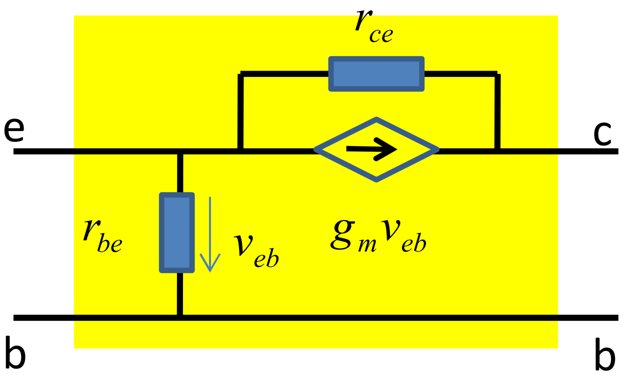
CB/CG组态
输入阻抗

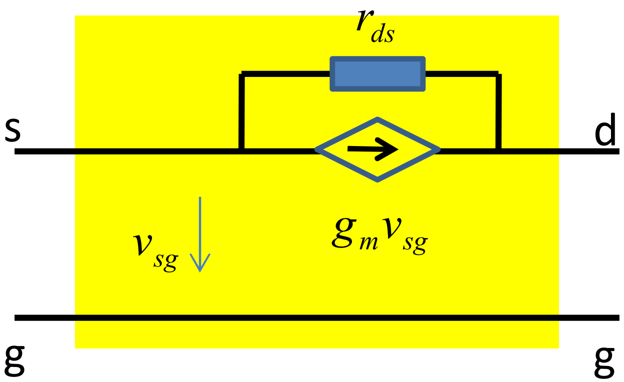


CB



CG





$$r_{in} = r_{be} \parallel \frac{R_L + r_{ce}}{1 + g_m r_{ce}}$$

$$Z_{01} \approx \frac{r_{be}}{\sqrt{\beta}}$$

$$r_{in} = \frac{R_L + r_{ds}}{1 + g_m r_{ds}}$$

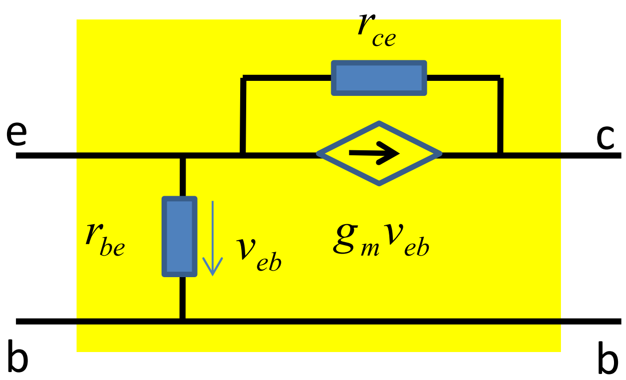
$$r_{out} = r_{be} \parallel R_S + r_{ce} + g_m (r_{be} \parallel R_S) r_{ce}$$

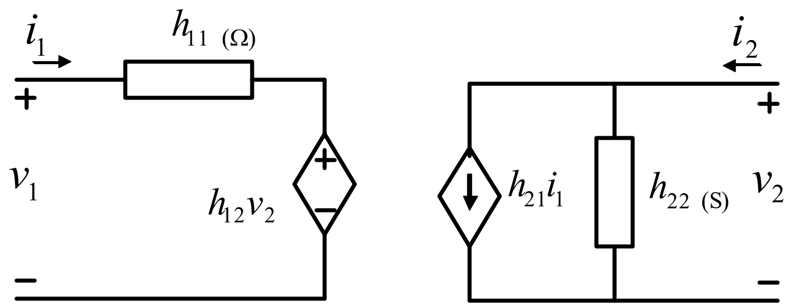
$$Z_{02} \approx \sqrt{\beta} r_{ce}$$

$$r_{out} = R_S + r_{ds} + g_m R_S r_{ds}$$

$$G_{pmax} = \frac{1}{(\sqrt{AD} + \sqrt{BC})^2} \approx \frac{1}{AD} \approx \frac{1}{A} \approx g_m r_{ce}$$

CB组态：电流缓冲器？





$$\mathbf{h}_{CB} = \begin{bmatrix} \dfrac{1}{g_m + g_{be} + g_{ce}} & \dfrac{g_{ce}}{g_m + g_{be} + g_{ce}} \\ -\dfrac{g_m + g_{ce}}{g_m + g_{be} + g_{ce}} & \dfrac{g_{be} g_{ce}}{g_m + g_{be} + g_{ce}} \end{bmatrix}$$

$$\mathbf{h} = \begin{bmatrix} 24.9314\Omega & 0.0002493 \\ -0.9975 & 0.02493\mu S \end{bmatrix}$$

g_m=40mS，r_{be}=10kΩ，r_{ce}=100kΩ

CB组态单向化条件

$$\mathbf{h}_{CB}=\begin{bmatrix}\dfrac{1}{g_m+g_{be}+g_{ce}} & \dfrac{g_{ce}}{g_m+g_{be}+g_{ce}}\\ -\dfrac{g_m+g_{ce}}{g_m+g_{be}+g_{ce}} & \dfrac{g_{be}g_{ce}}{g_m+g_{be}+g_{ce}}\end{bmatrix}$$

$$\left|h_{12}h_{21}\right|<<\left|(R_S+h_{11})(G_L+h_{22})\right|$$

$$(g_m+g_{ce})g_{ce}<<\left(R_S(g_m+g_{be}+g_{ce})+1\right)\left(G_L(g_m+g_{be}+g_{ce})+g_{be}g_{ce}\right)$$

$\Updownarrow$ $g_m>>g_{be},g_{ce}$ 自然满足

$$g_mg_{ce}<<(R_Sg_m+1)(G_Lg_m+g_{be}g_{ce})$$

$\Updownarrow$

$$(R_Sg_m+1)\left(\frac{r_{ce}}{R_L}+\frac{1}{\beta}\right)>>1 \Leftarrow R_L<<r_{ce}$$

充分而非必要条件

$\Downarrow$ 教材习题4.14分析

CB组态单向化

$R_L << r_{ce}$ 充分条件

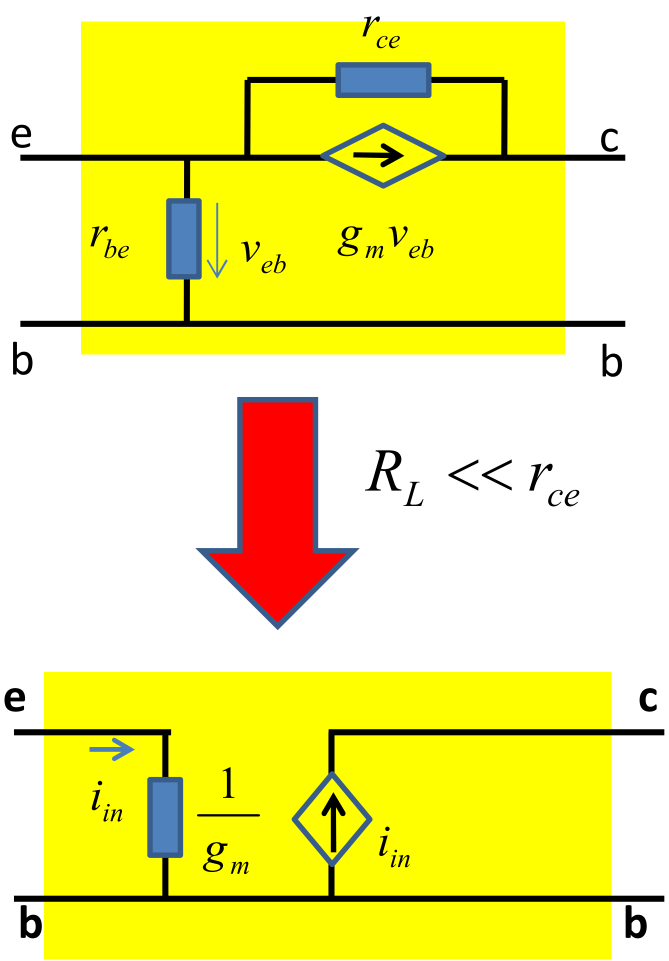
$$\mathbf{h}_{CB}=\begin{bmatrix}\dfrac{1}{g_m+g_{be}+g_{ce}} & \dfrac{g_{ce}}{g_m+g_{be}+g_{ce}}\\ -\dfrac{g_m+g_{ce}}{g_m+g_{be}+g_{ce}} & \dfrac{g_{be}g_{ce}}{g_m+g_{be}+g_{ce}}\end{bmatrix}$$

$$\overset{R_L<<r_{ce}}{\approx}\begin{bmatrix}\dfrac{1}{g_m+g_{be}+g_{ce}} & 0\\ -\dfrac{g_m+g_{ce}}{g_m+g_{be}+g_{ce}} & \dfrac{g_{be}g_{ce}}{g_m+g_{be}+g_{ce}}\end{bmatrix}$$

$$\approx\begin{bmatrix}\dfrac{1}{g_m} & 0\\ -1 & 0\end{bmatrix}$$

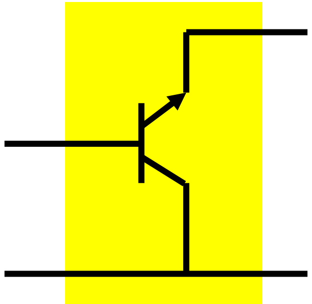
$$r_{out}=r_{be}+r_{ce}+g_m r_{be} r_{ce}$$

40MΩ极大：可认为开路

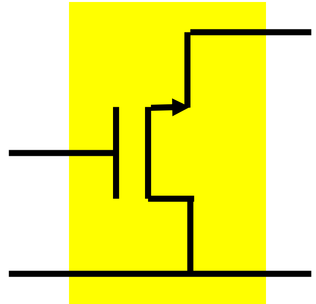


电流缓冲器模型

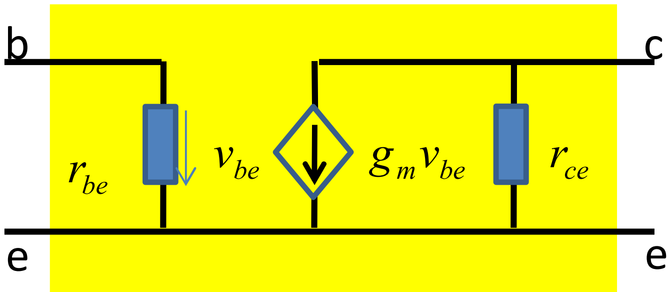
2.3 CC/CD组态

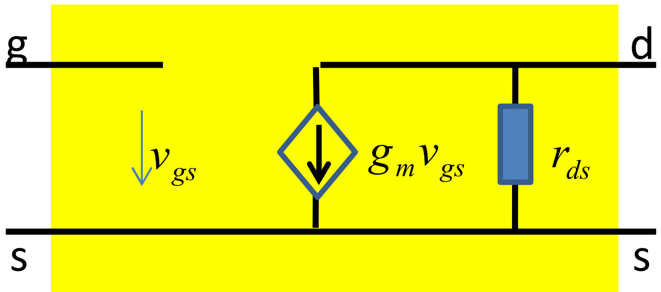


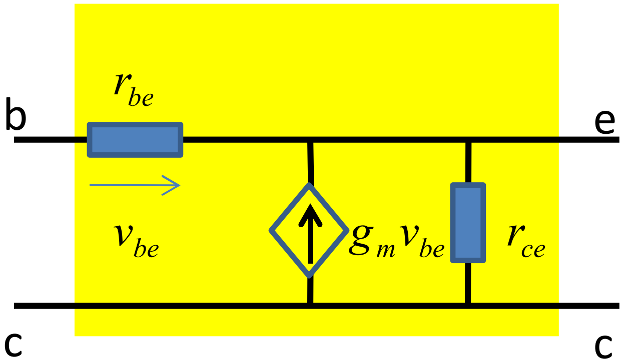
CC

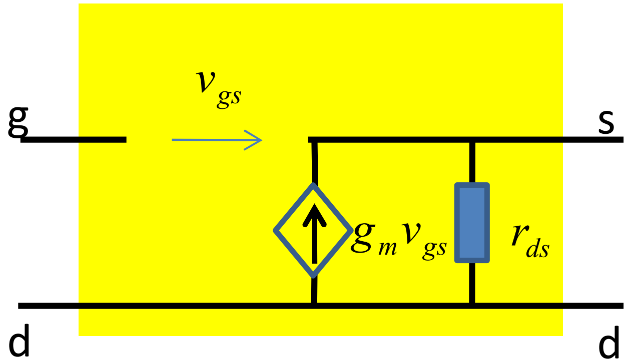


CD

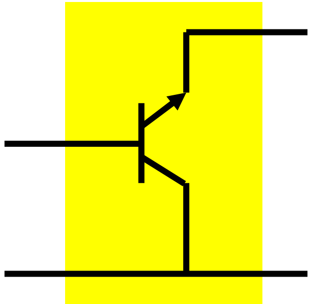




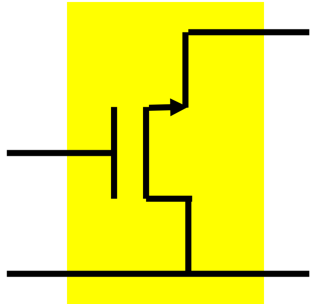




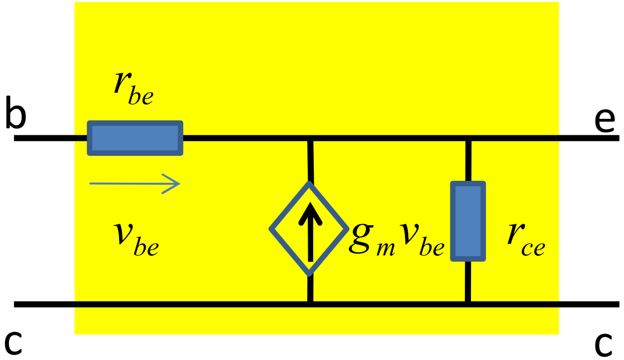
CC/CD组态
输入阻抗

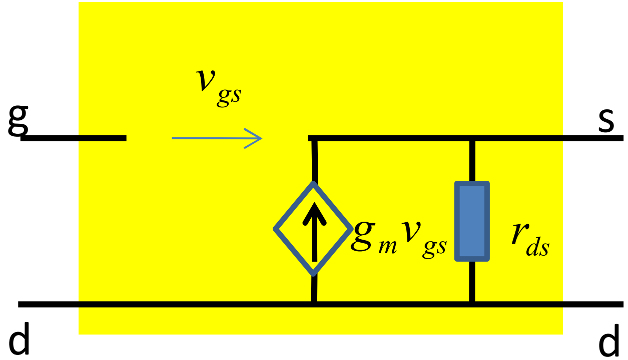


CC



CD





$$r_{in} = r_{be} + r_{ce} \| R_L + g_m r_{be}\left(r_{ce} \| R_L\right)$$

$$Z_{01} \approx \sqrt{A_{v0}}\, r_{be}$$

$$R_{in} \to \infty$$

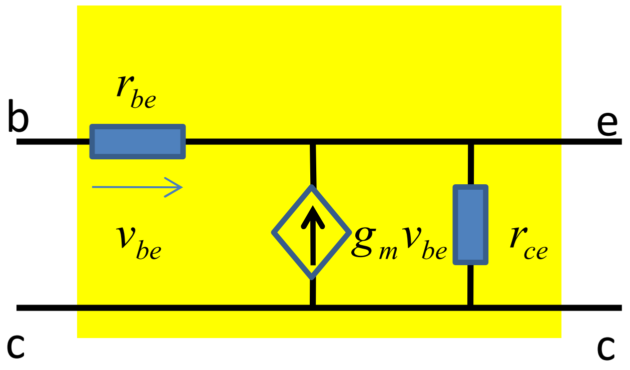
$$R_{out} = r_{ce} \| \frac{r_{be} + R_S}{1 + g_m r_{be}}$$

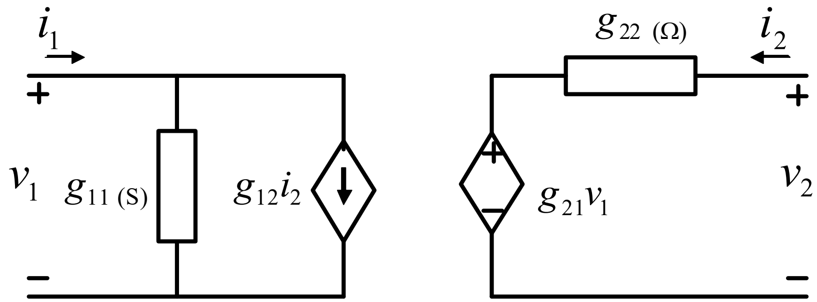
$$Z_{02} \approx \frac{r_{ce}}{\sqrt{A_{v0}}}$$

$$R_{out} = ?\, r_{ds} \| \frac{1}{g_m}$$

$$G_{pmax} = \frac{1}{\left(\sqrt{AD} + \sqrt{BC}\right)^2} \approx \frac{1}{AD} \approx \frac{1}{\mathrm{D}} \approx g_m r_{be}$$

CC组态：电压缓冲器？





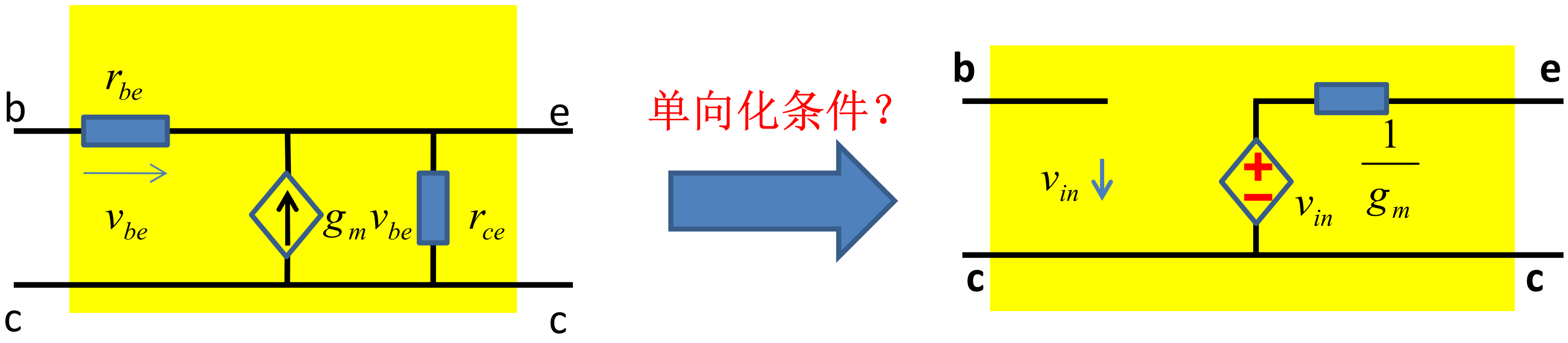
$$[g]_{CC} = \begin{bmatrix} \dfrac{g_{be} g_{ce}}{g_m + g_{be} + g_{ce}} & \dfrac{-g_{be}}{g_m + g_{be} + g_{ce}} \\ \dfrac{g_m + g_{be}}{g_m + g_{be} + g_{ce}} & \dfrac{1}{g_m + g_{be} + g_{ce}} \end{bmatrix}$$

$$\mathbf{g} = \begin{bmatrix} 0.0249\,\mu S & -0.00249 \\ 0.9998 & 24.9314\Omega \end{bmatrix}$$

g_m=40mS，r_{be}=10kΩ，r_{ce}=100kΩ

练习题 CC组态电压缓冲器模型

- （1）分析g参量矩阵应用的单向化条件
- （2）确认CC组态晶体管的单向化条件
  - 可以是充分非必要条件
- （3）说明在满足该单向化条件情况下，CC组态为电压缓冲器模型

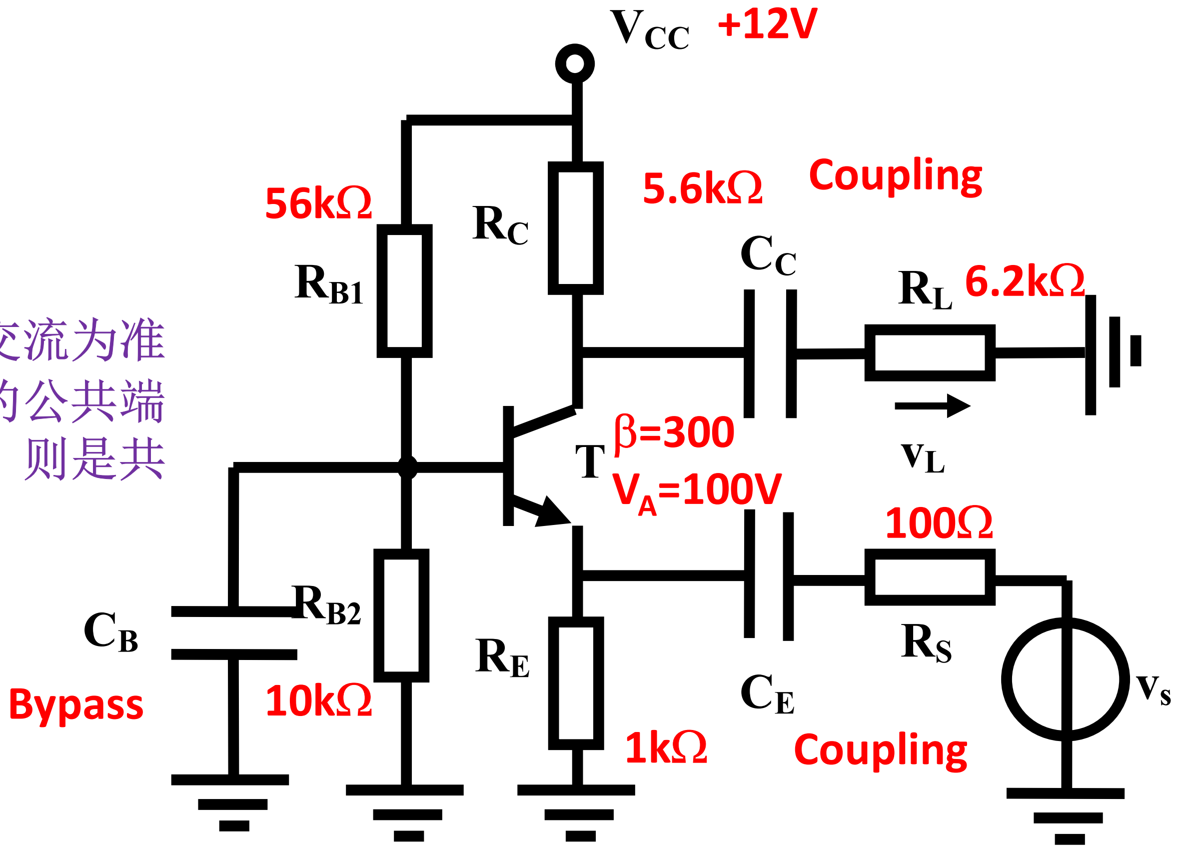


2.4 BJT组态总结

	CE	CB	CC
输入阻抗	r_{be}	$r_{be} \parallel \dfrac{R_L + r_{ce}}{1 + g_m r_{ce}}$	$r_{be} + r_{ce} \parallel R_L + g_m r_{be}\left(r_{ce} \parallel R_L\right)$
输出阻抗	r_{ce}	$r_{be} \parallel R_S + r_{ce} + g_m\left(r_{be} \parallel R_S\right) r_{ce}$	$r_{ce} \parallel \dfrac{r_{be} + R_S}{1 + g_m r_{be}}$
最大功率增益	$\dfrac{1}{4} g_m r_{ce} \cdot \beta$	$\sim\prec g_m r_{ce}$	$\sim\prec \beta = g_m r_{be}$
理想模型	反相跨导 **G_{m0} =-g_m**	电流缓冲 **A_{i0}=1**	电压缓冲 **A_{v0}=1**
输入输出阻抗	r_{be} r_{ce}	$r_{in} \approx 1/g_m$	$r_{out} \approx 1/g_m$
单向化条件		$R_L << r_{ce}$ 充分非必要	$R_S << r_{be}$

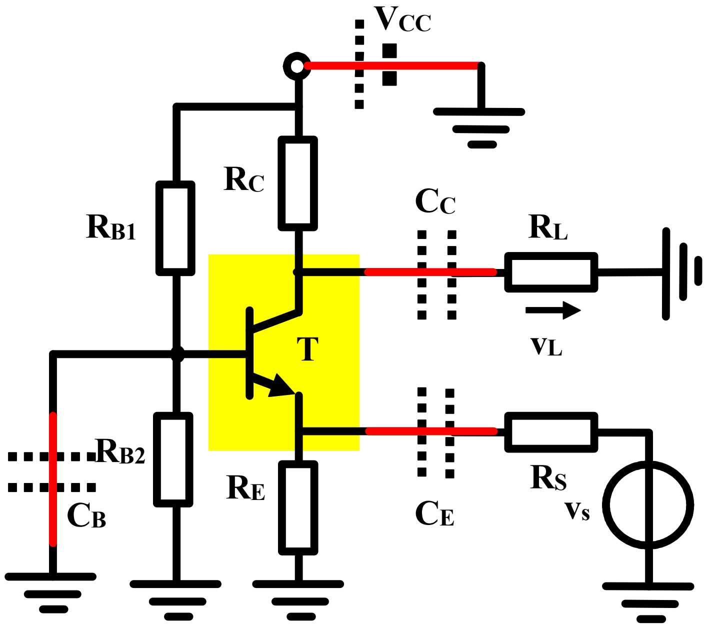
例4 CB组态交流小信号放大器分析

组态是以交流为准交流分析的公共端点是基极，则是共基组态

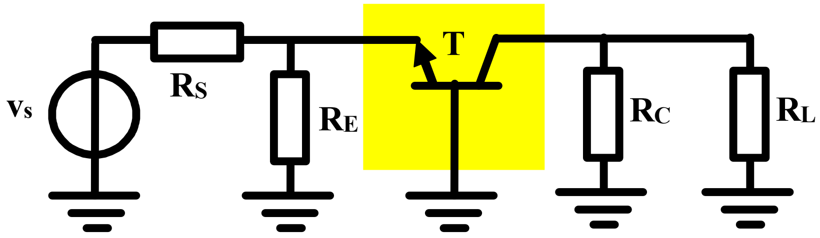


$$A_v = \frac{v_L}{v_S} = ?$$

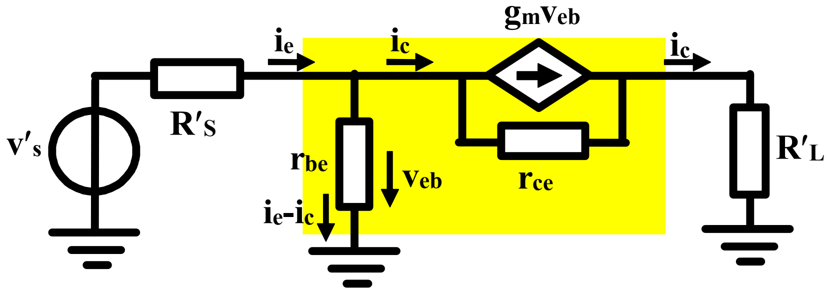
交流小信号线性分析



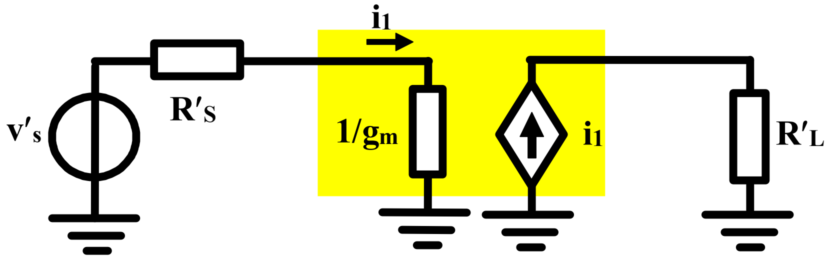
（a）耦合电容、直流偏置电压源交流短路



（b）交流小信号分析电路



（c）晶体管采用通用跨导器模型



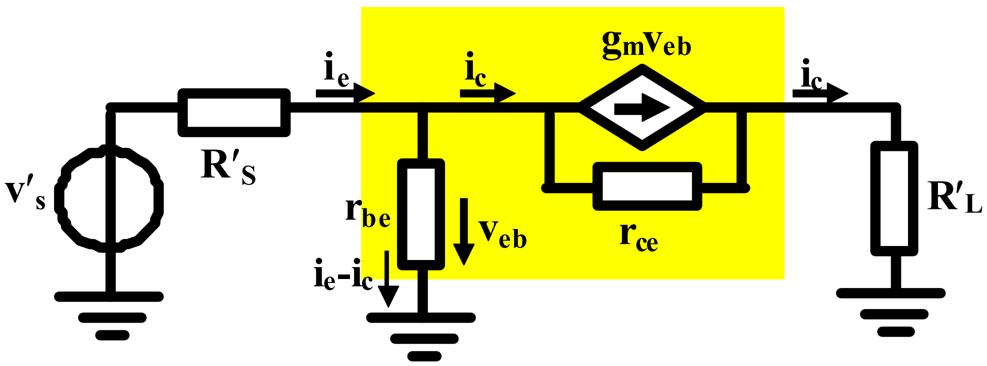
（d）晶体管采用 CB 组态电流缓冲器模型

$$v_s' = \frac{R_E}{R_E + R_S} v_s = \frac{1k}{1k + 0.1k} v_s = 0.909 v_s$$

$$R_L' = R_L \parallel R_C = 6.2k\Omega \parallel 5.6k\Omega = 2.94k\Omega$$

$$R_S' = R_S \parallel R_E = \frac{R_E R_S}{R_E + R_S} = \frac{1k \times 0.1k}{1k + 0.1k} = 90.9\Omega$$

晶体管用y参量电路模型



跨导器模型

$$v'_s = R'_S i_e + (i_e - i_c) r_{be}$$

$$v'_s = R'_S i_e + (i_c - g_m (i_e - i_c) r_{be}) r_{ce} + i_c R'_L$$

$$v_L = i_c R'_L = \frac{(1+g_m r_{ce}) r_{be} R'_L}{R'_S (r_{be} + r_{ce} + g_m r_{be} r_{ce} + R'_L) + r_{be} (r_{ce} + R'_L)} v'_s$$

$$= \frac{(1+41.5m \times 92.6k) \times 7.22k \times 2.94k}{90.9 \times (7.22k + 92.6k + 41.5m \times 7.22k \times 92.6k + 2.94k) + 7.22k \times (92.6k + 2.94k)} v'_s$$

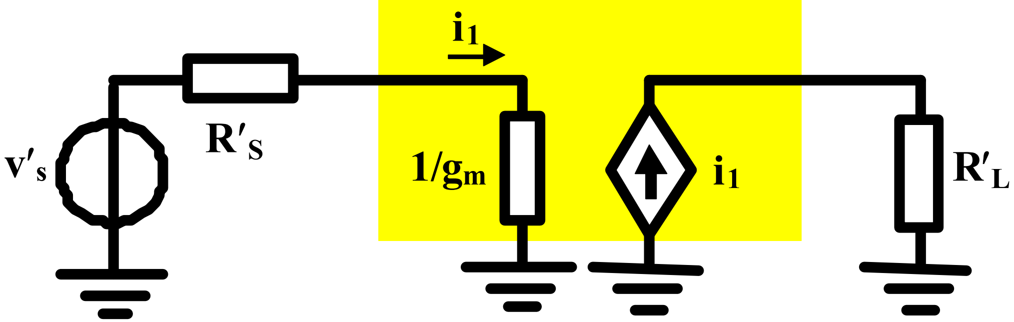
$$= 25.3 \times v'_s = 25.3 \times 0.909 v_s = 23 v_s$$

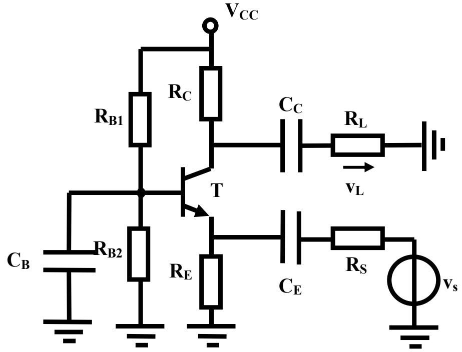
同相电压放大

27.2dB

晶体管采用CB电流缓冲器模型

$$R'_L = 2.94k\Omega << r_{ce} = 92.6k\Omega$$





$$i_1 = \frac{v'_s}{R'_S + \dfrac{1}{g_m}} = \frac{g_m}{1 + g_m R'_S} v'_s = g_{mf} v'_s$$

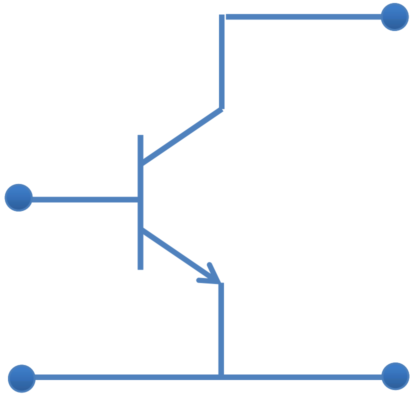
$$v_L = i_1 R_L = \frac{g_m R'_L}{1 + g_m R'_S} v'_s = g_{mf} R'_L v'_s$$

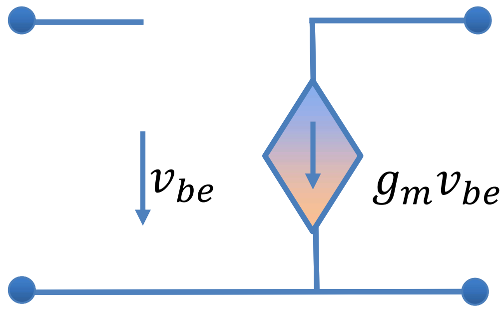
$$= \frac{41.5m \times 2.94k}{1 + 41.5m \times 0.091k} \times 0.909 v_s = \frac{122}{1 + 3.77} \times 0.909 v_s = 23.2$$

27.3dB的同相电压放大

我们总是喜欢简单模型：结论简洁，易于记忆

作业1 理想晶体管





理想晶体管模型为理想压控流源。

1）列写含有串串负反馈电阻的**CE**组态理想晶体管的端口约束方程，并将其转化为二端口等效电路

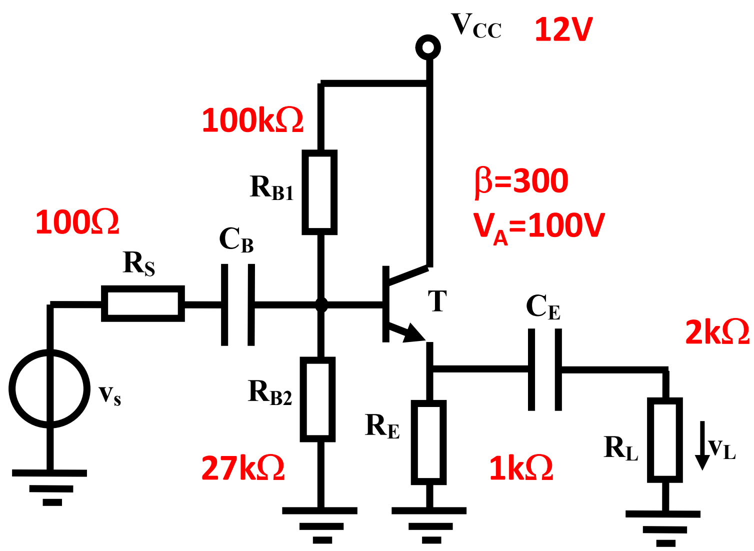
2）列写**CB**组态理想晶体管的端口约束方程，并将其转化为二端口等效电路

3）列写**CC**组态理想晶体管的端口约束方程，并将其转化为二端口等效电路

4）前述三个二端口网络，端口**1**对接戴维南源（v_s，R_s），端口**2**对接负载电阻R_L，分析电压增益$Av=v_L/v_s$

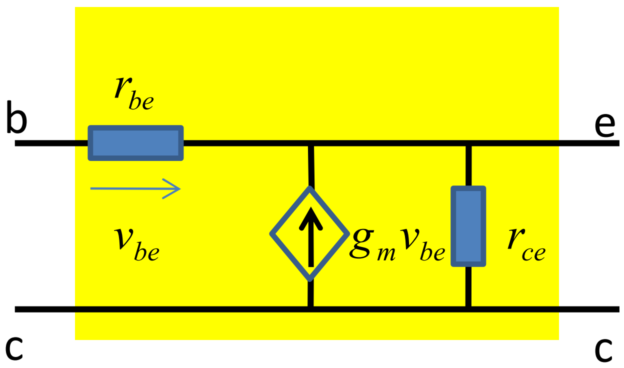
作业2
CC组态放大器

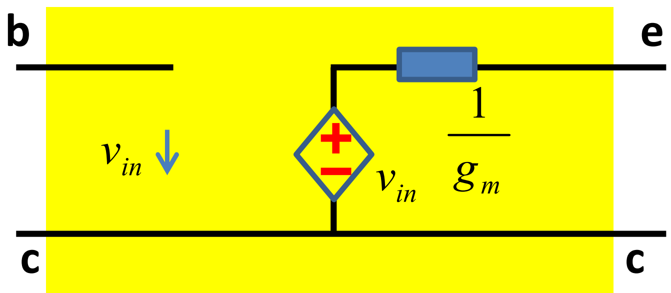
- （1）直流分析
- （2）交流分析
  - 采用y参量跨导器模型分析
  - 采用CC电压缓冲器模型分析



$$A_v = \frac{v_L}{v_S} = ?$$

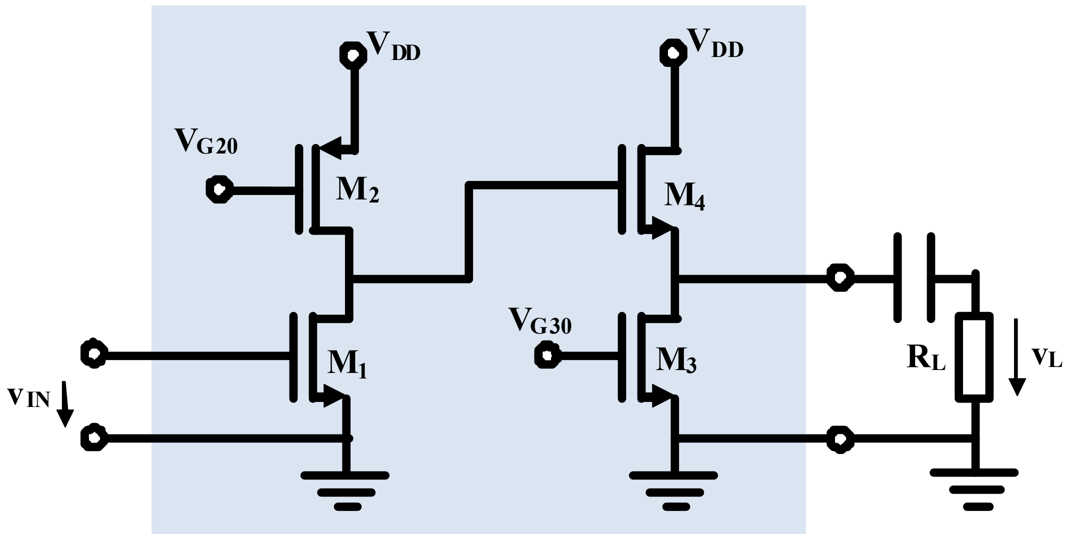
$$A_i = \frac{i_L}{i_S} = \frac{i_L}{G_S v_S} = ?$$



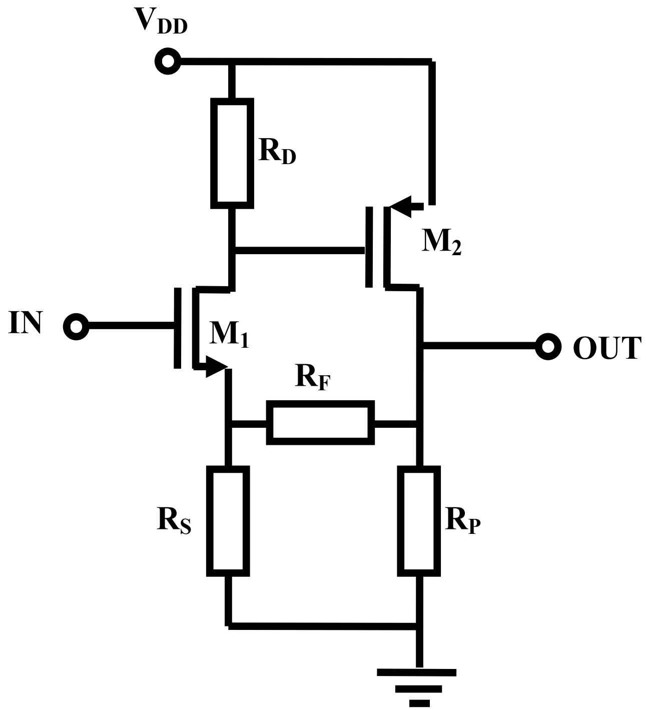


作业3

- 请画出图示电路的交流小信号分析电路模型，求电压放大倍数，输入电阻、输出电阻，及源端到负载端二端口等效电路
  - 假设晶体管工作在恒流区，交流分析用**y**参量微分元件替代
  - 二端口总网络用电压放大器最适**g**参量描述

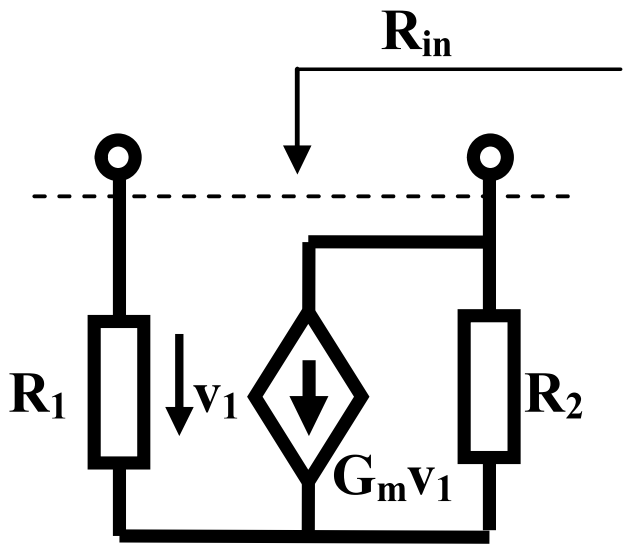


作业4、5



- **4**、**p20**： 三句话说清楚负反馈放大器
  - 数学分析过程和结论
  - 具有将上述数学操作转换为电路操作的能力
- **5**、对负反馈放大器分析的具体电路操作
- 习题**4.23** 一个负反馈放大器的分析：对于如图**E4.8.25**所示负反馈放大电路。
  - （**1**）找到负反馈闭合环路并加以描述，说明闭环上某一点电压的波动，环路一周后其波动被抑制，从而说明这是一个负反馈连接形式。
  - （**2**）判定其负反馈连接方式，说明该负反馈连接方式决定的受控源类型，进而获得反馈系数表达式，并给出深度负反馈情况下的闭环增益表达式。
  - （**3**）假设两个晶体管在恒流区的交流小信号电路模型为理想压控流源，其跨导增益分别为g_{m1}和g_{m2}，请给出开环增益表达式。

作业6 bc端等效电阻



用加流求压法证明：

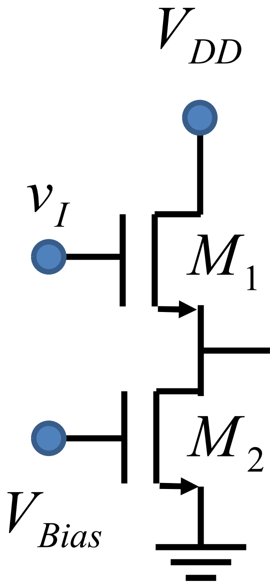
$$R_{in} = R_1 \langle G_m \rangle R_2 = R_1 + R_2 + G_m R_1 R_2$$

对于**BJT**晶体管，则有

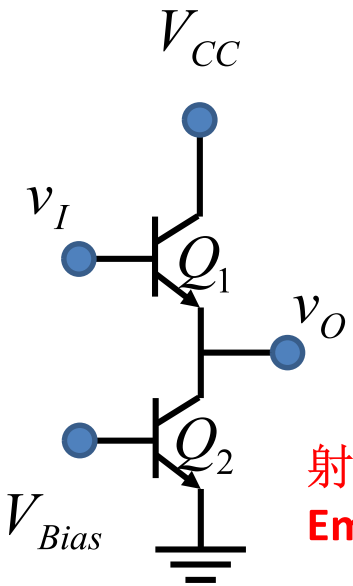
$$r_{bc,in} = r_{be} \langle g_m \rangle r_{ce}$$
$$= r_{be} + r_{ce} + g_m r_{be} r_{ce}$$
$$\approx g_m r_{be} r_{ce}$$

牢记这个结论：经常会用

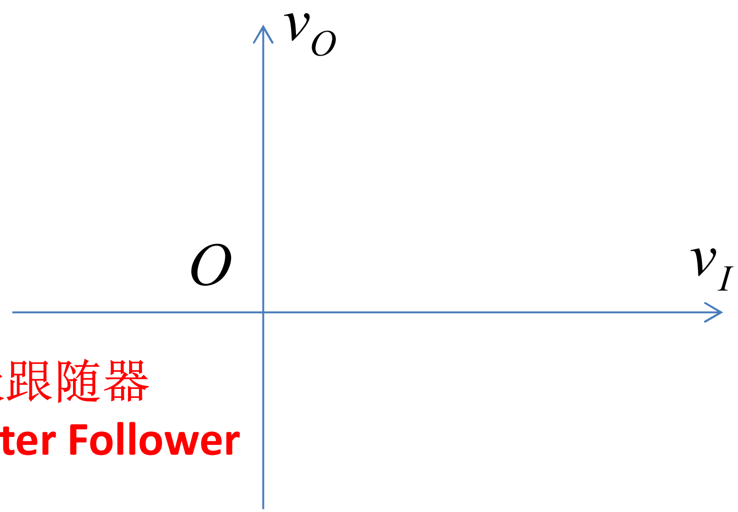
作业7 射极跟随器



源极跟随器
Source Follower



射极跟随器
Emitter Follower

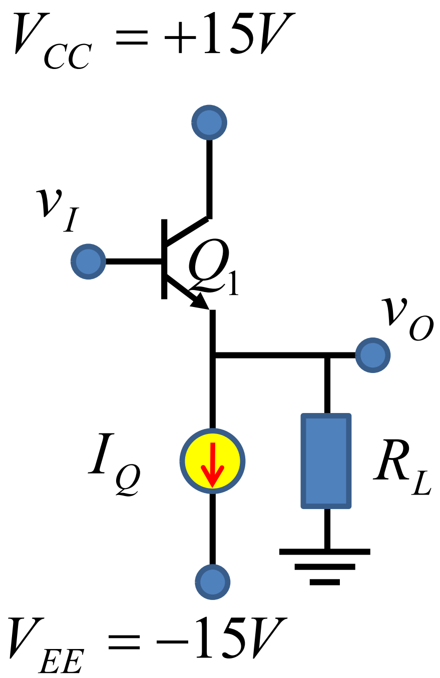


假设所有晶体管均位于有源区，证明： $r_o \approx \dfrac{1}{g_{m1}}$

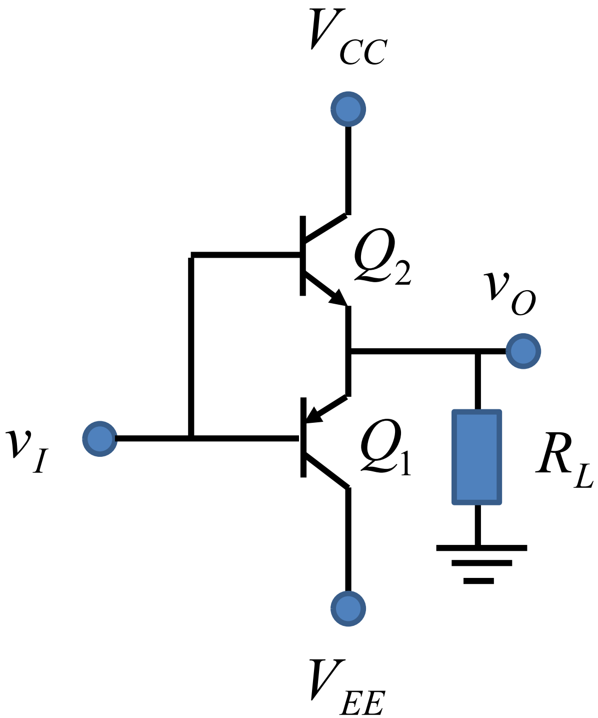
用分段折线模型，分析射极跟随器的输入输出电压转移特性曲线
问输入直流电压为多大时，跟随器线性度最高

作业8 输出级

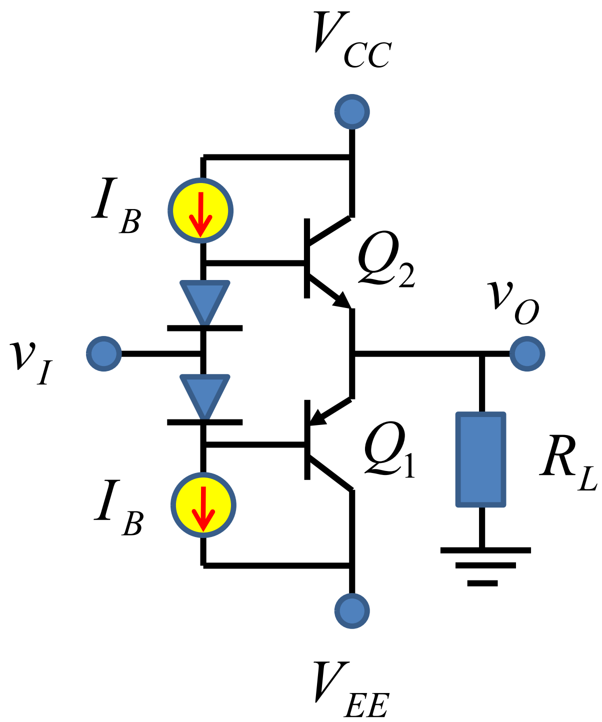
- 这里有三个转移特性曲线，试分析这三条转移特性曲线分别对应哪种输出级，说明为什么会形成这样的转移特性曲线，并将正确的表达式列写于图上问号位置
  - A类射极跟随器
  - B类推挽结构
  - AB类推挽结构



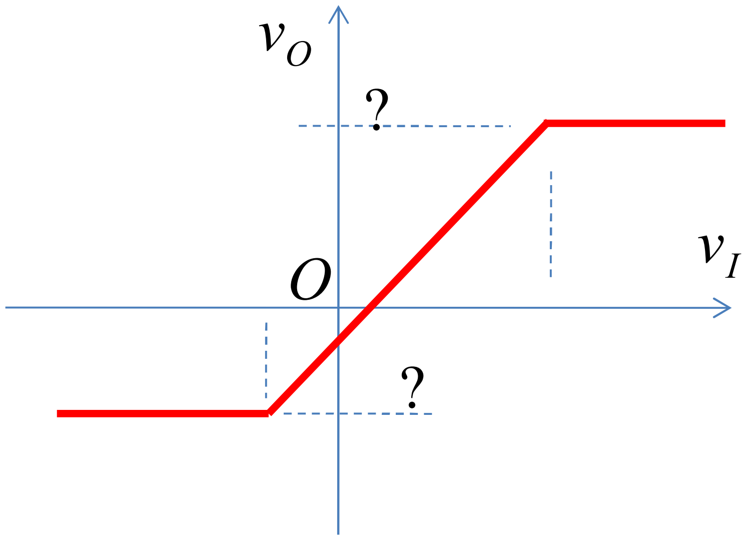
A类射极跟随器

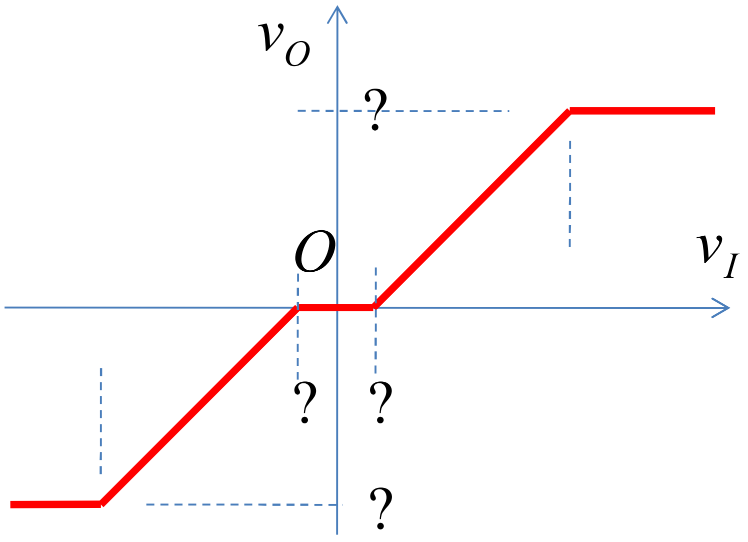


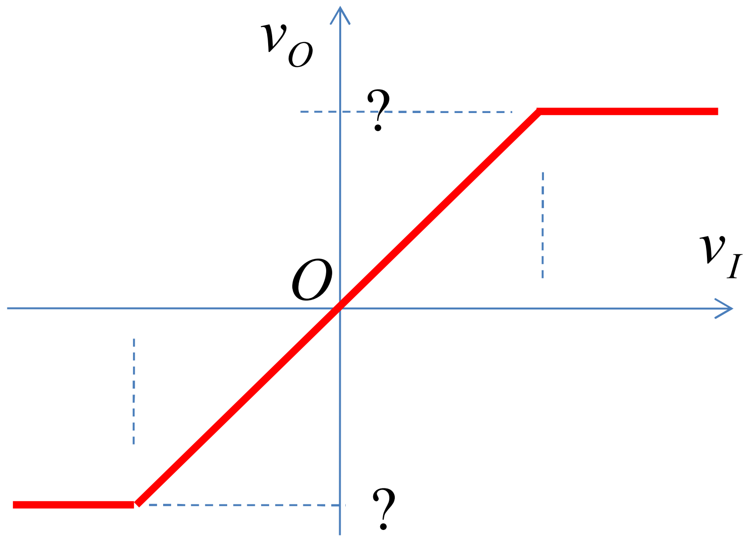
B类推挽



AB类推挽


v_O
?
v_I
O
?


v_O
?
O
v_I
?
?
?


v_O
?
O
v_I
?

CAD作业

- 对作业**8**进行仿真，给出输入输出转移特性曲线，和理论分析结果进行比对
  - 库中如果没有**BJT**，选用**MOS**，思考如何给出**AB**类的微微导通偏置电压？