电子电路与系统基础I

习题课第八讲

第五周作业讲解（部分）
第六周作业讲解（部分）

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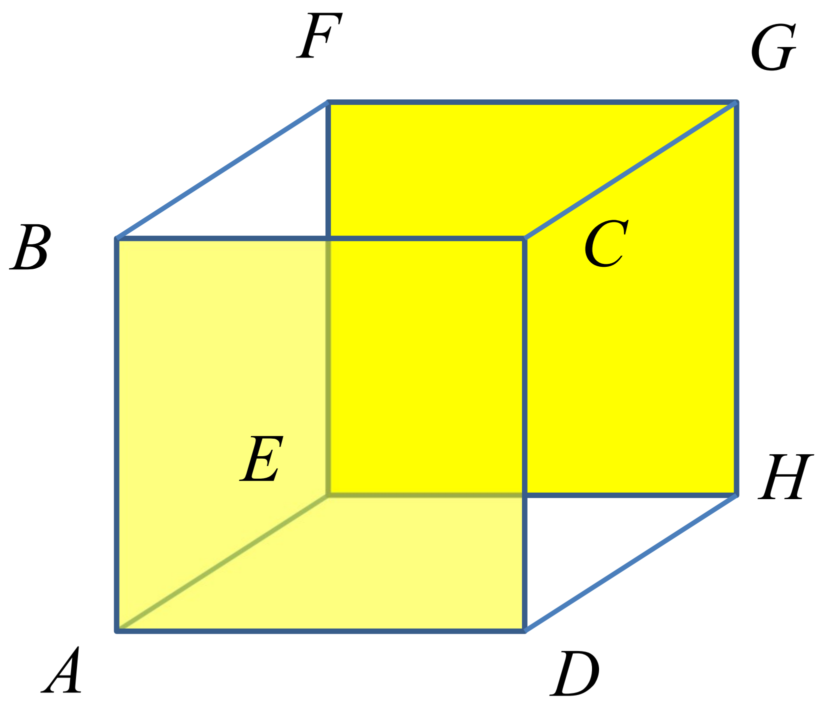
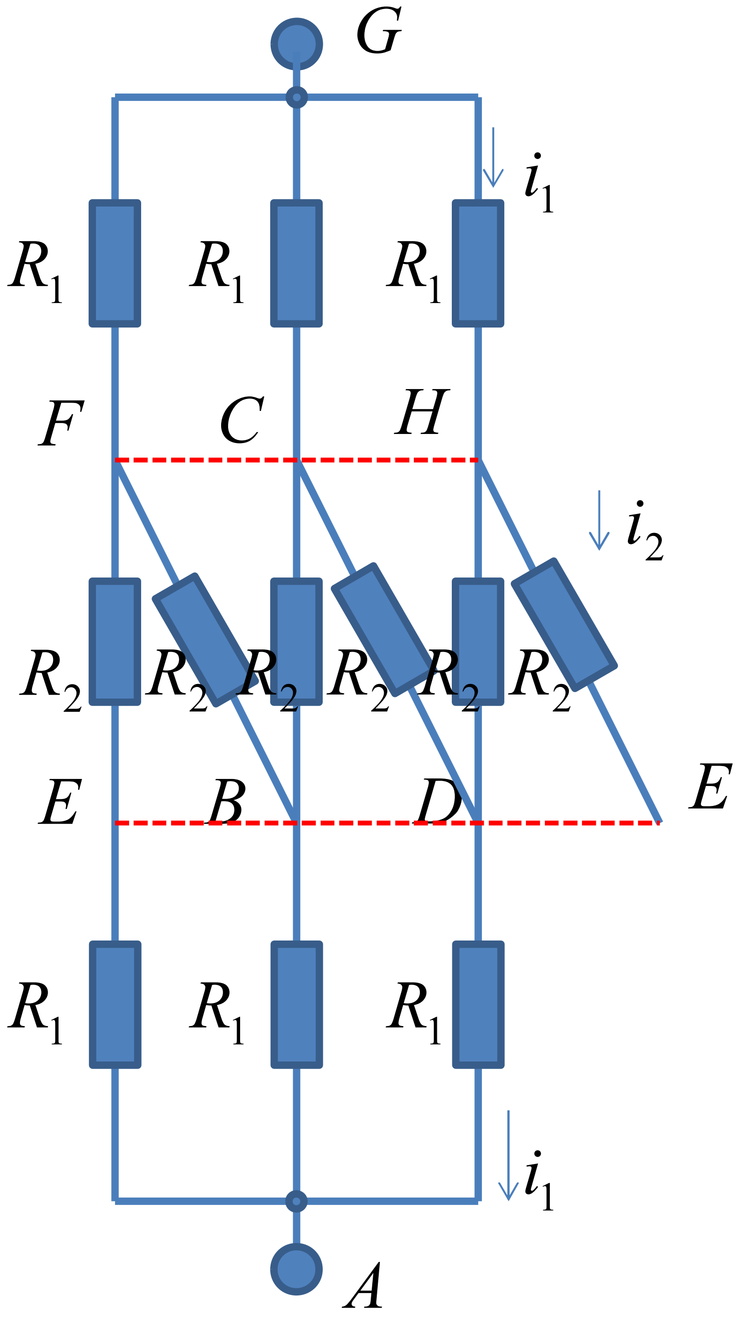
第5周作业

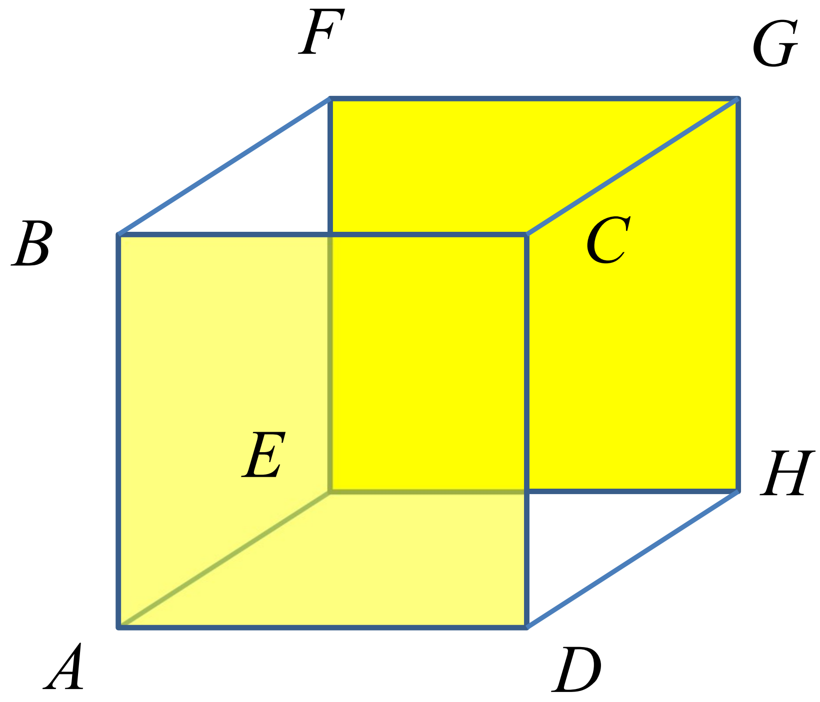
作业2 直观的理解力

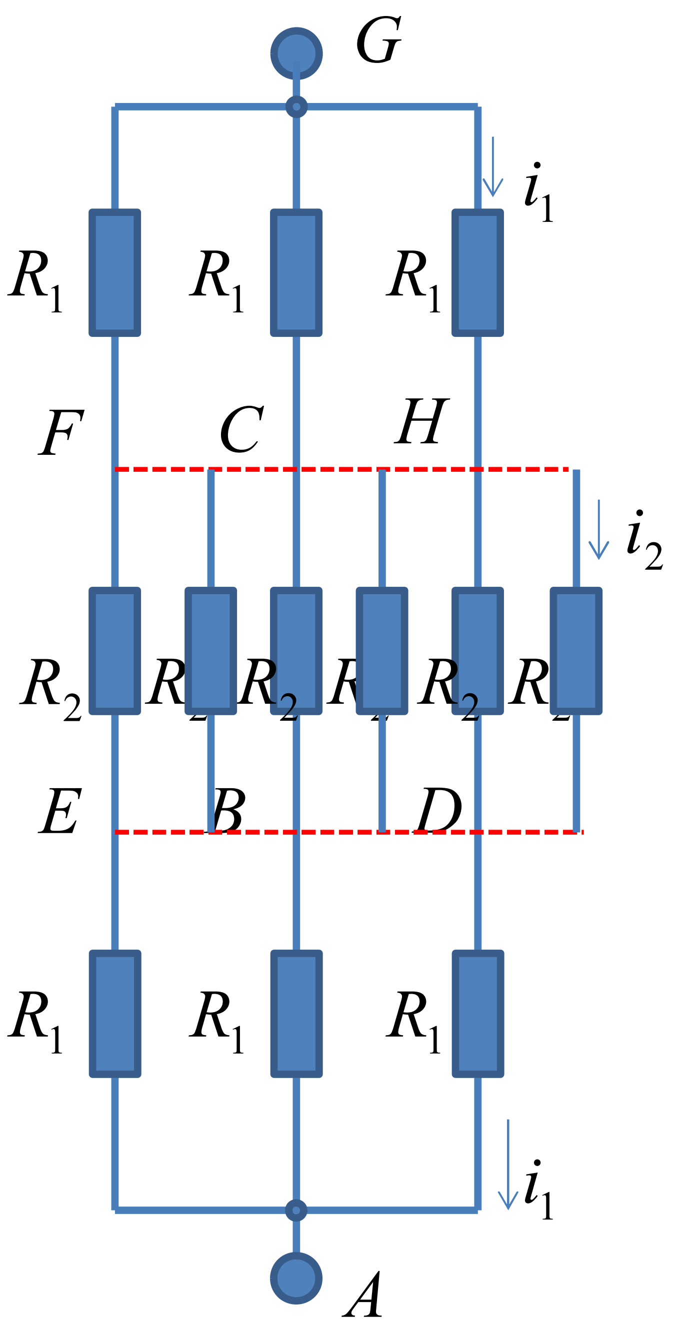
- 这是一个立方体盒子，每条边为一根金属丝电阻，现希望在对角顶点**AG**两端加上一个电源电压，立方体的**12**条边上有相同的热量发出，用于加热这个盒子内部空间。请问**12**条边上的电阻阻值具有什么样的关系才能达到热量均匀分布**12**条边的设计目标？你是如何直观地分析出这个结论的？
  - 如果不能直观分析，请列出数学表达式证明你的结论或推导出你的结论。
  - 假设**AG**两端所加电压为**220V$_{rms}$**交流电，从**A**到**G**为一个**1kW**的加热器，则**12**条边上的具体电阻阻值为多大？



拓扑结构
对称性







对称性

电流一分为二

$$i_1 = 2i_2$$

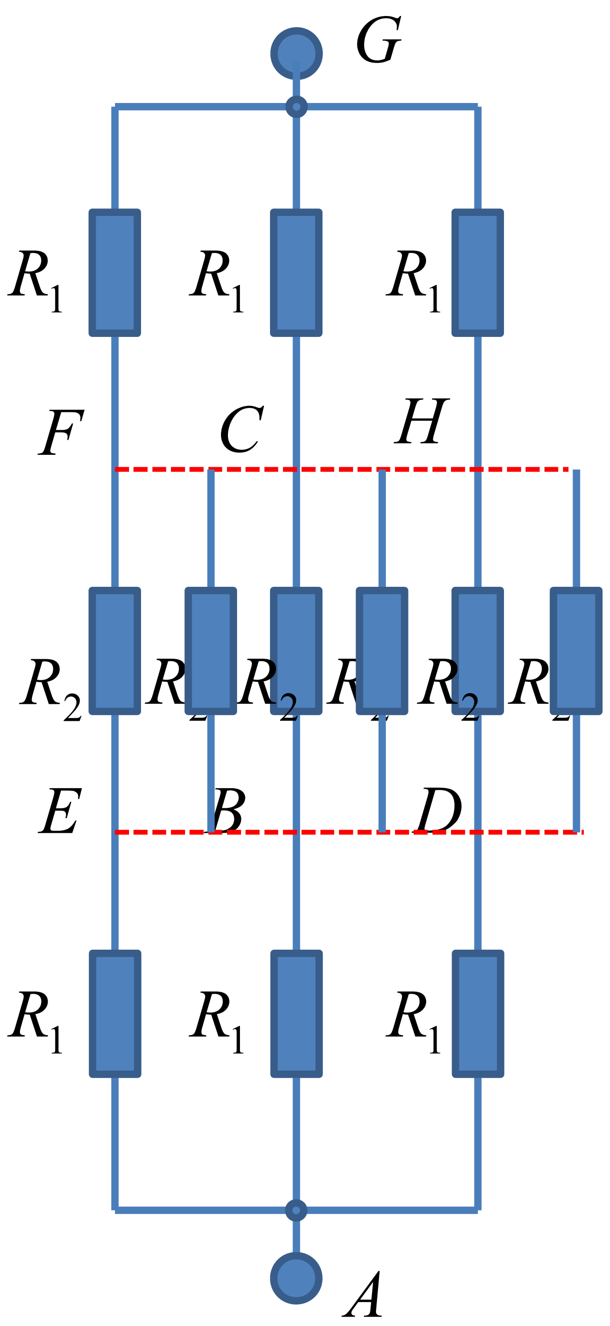
释放相同的热量：吸收相同的电功率

$$P = I_{1,rms}^2 R_1$$

$$= I_{2,rms}^2 R_2 = \frac{1}{4} I_{1,rms}^2 R_2$$

⇨ $R_2 = 4R_1$

直观解释：电流为**1/2**，电阻必须**4**倍才具有相同的功耗



$$R = \frac{1}{3}R_1 + \frac{1}{6}R_2 + \frac{1}{3}R_1$$

$$= \frac{1}{3}\cdot\frac{1}{4}R_2 + \frac{1}{6}R_2 + \frac{1}{3}\cdot\frac{1}{4}R_2 = \frac{1}{3}R_2$$

$$P = \frac{V_{rms}^2}{R} = 1kW = \frac{220^2}{\frac{1}{3}R_2}$$

$$R_2 = 3\times\frac{220^2}{1000} = 145.2\Omega$$

$$R_1 = \frac{1}{4}R_2 = 36.3\Omega$$

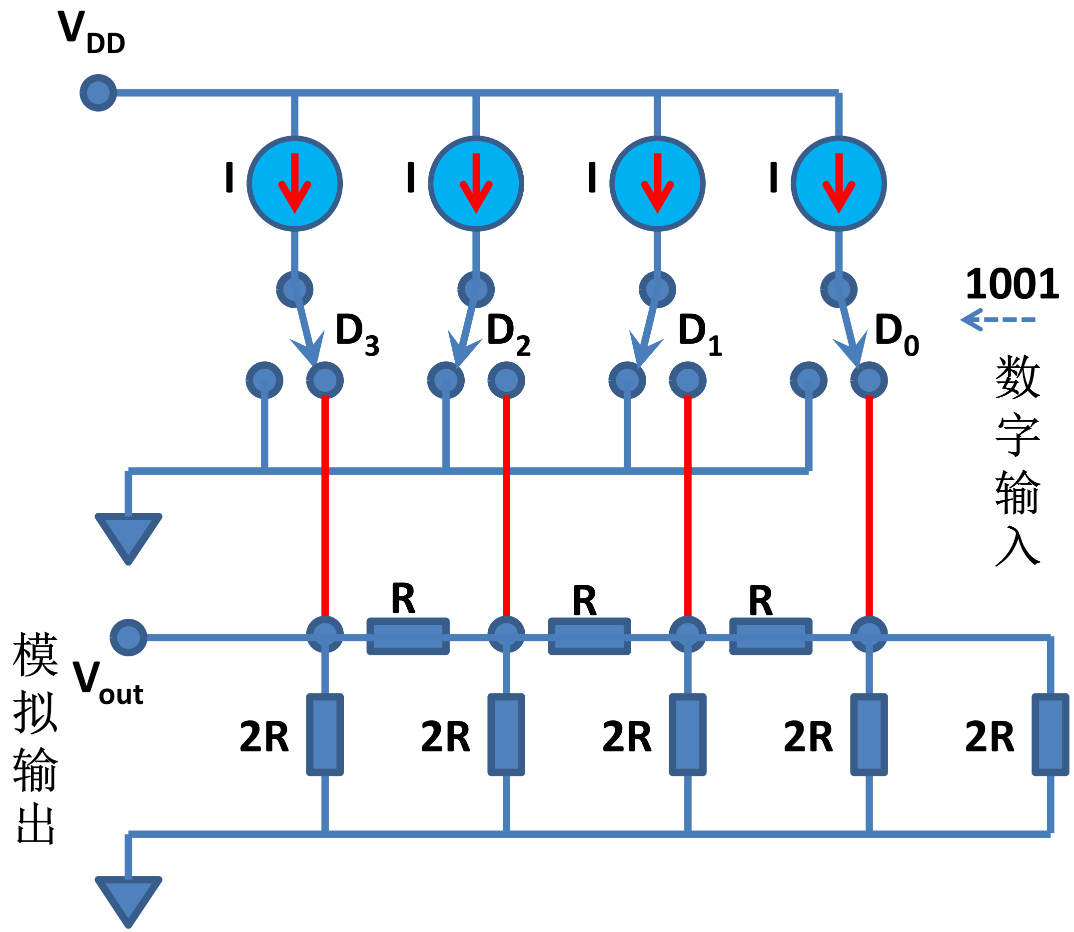
短路、开路替代的应用

- 电路如果具有某种对称结构、或平衡结构（如电桥），则可直接给出短路、开路替代，简化电路分析
  - 开路两点电压相等可短路替代
  - 短路两点电流为零可开路替代

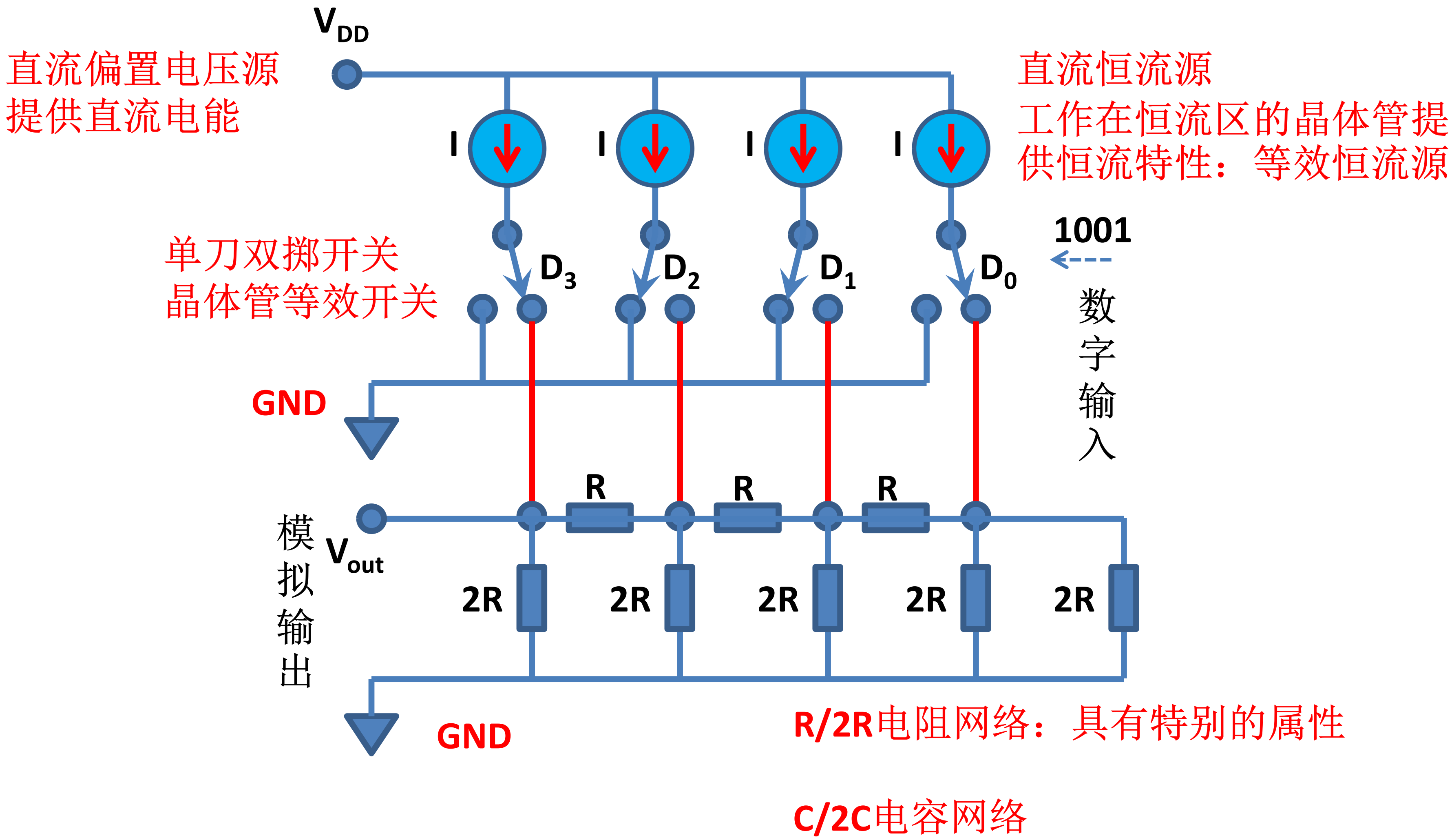
  - 理想运放输入端只能‘虚短’，不能用短路线替代，原因在于短路替代后可能存在短路电流，不满足‘虚断’特性

作业4：电路定理的应用练习

- 请分析确认该电路具有DAC功能？
  - 可采用戴维南-诺顿定理简化分析
  - 其他任意方法分析亦可

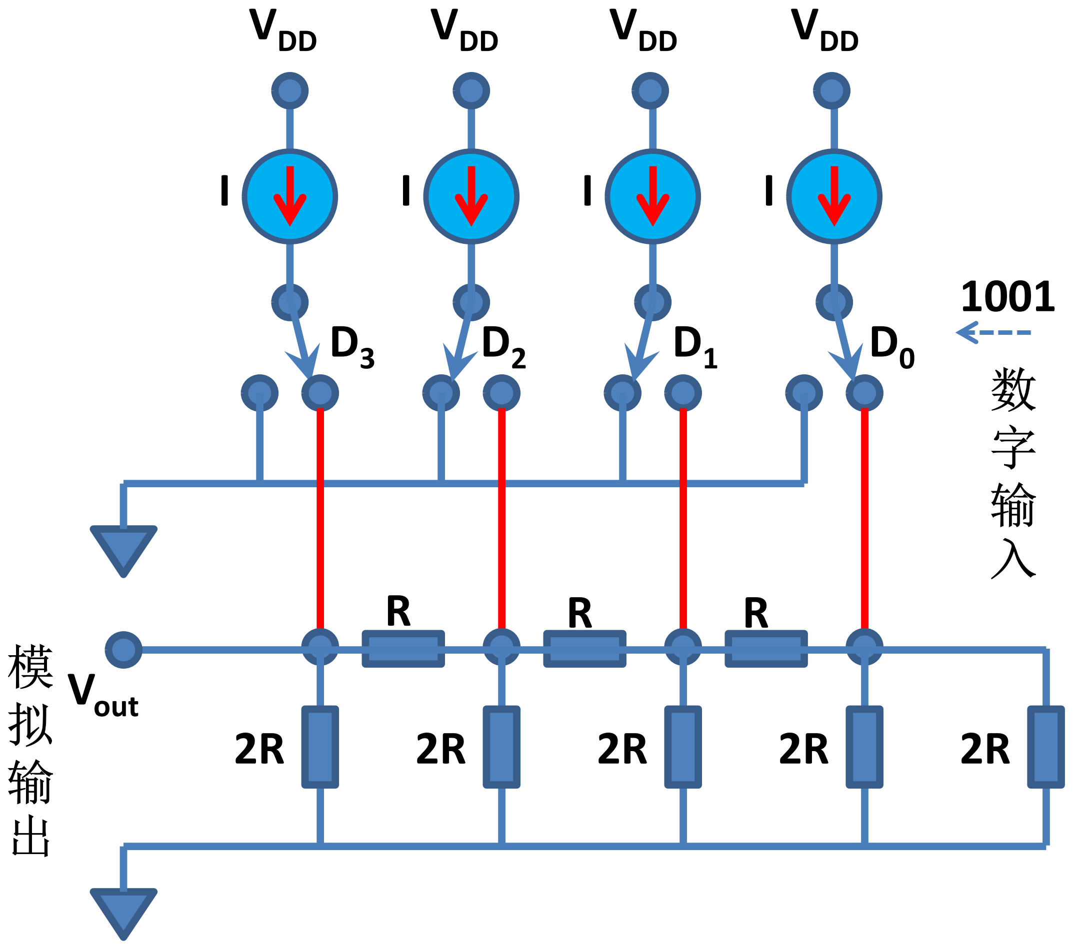


电路构件



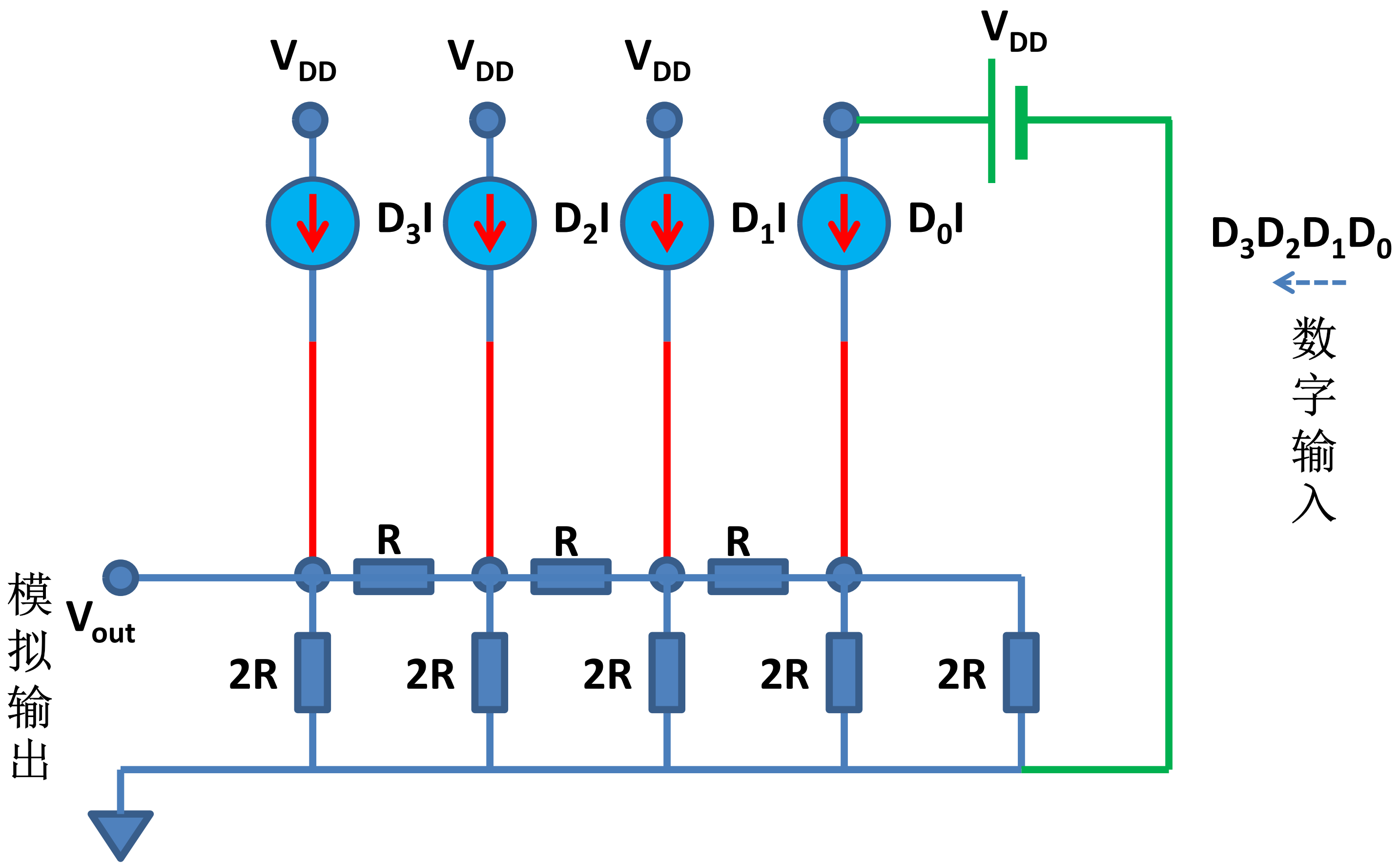
V_DD
直流偏置电压源
提供直流电能
直流恒流源
工作在恒流区的晶体管提供恒流特性：等效恒流源
I
I
I
I
单刀双掷开关
晶体管等效开关
D3
D2
D1
D0
1001
数字输入
GND
R
R
R
模拟输出
Vout
2R
2R
2R
2R
2R
GND
R/2R电阻网络：具有特别的属性
C/2C电容网络

分离：替代定理



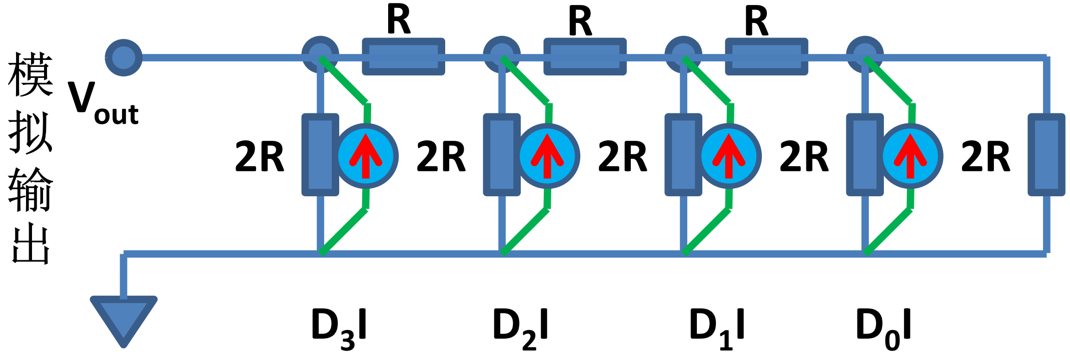
V_DD
V_DD
V_DD
V_DD
I
I
I
I
D3
D2
D1
D0
1001
数字输入
R
R
R
模拟输出
Vout
2R
2R
2R
2R
2R

恒流源

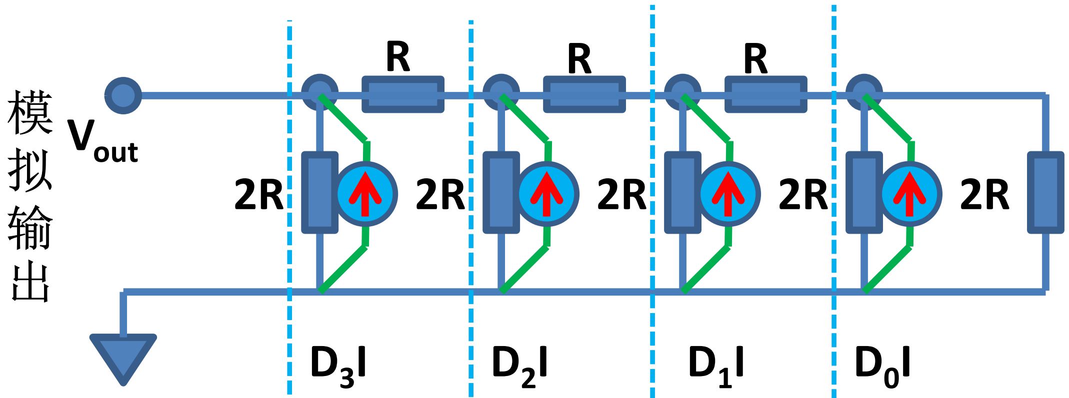


V_DD
V_DD
V_DD
V_DD
D3I
D2I
D1I
D0I
D3D2D1D0
数字输入
R
R
R
2R
2R
2R
2R
2R
模拟输出
Vout

电源合并：替代定理



戴维南-诺顿定理



$$V_{out} = v_{TH} = i_N R_N$$

$$= \left(D_3 + \frac{1}{2} D_2 + \frac{1}{4} D_1 + \frac{1}{8} D_0 \right) IR$$

$$= \left(2^3 D_3 + 2^2 D_2 + 2^1 D_1 + 2^0 D_0 \right) \frac{IR}{8}$$

$$= \Delta V \sum_{k=0}^{n-1} 2^k D_k$$

n=4bit DAC

$$R_N = R$$

$$i_N = D_0 I$$

$$R_N = R$$

$$i_N = D_1 I + \frac{1}{2} D_0 I$$

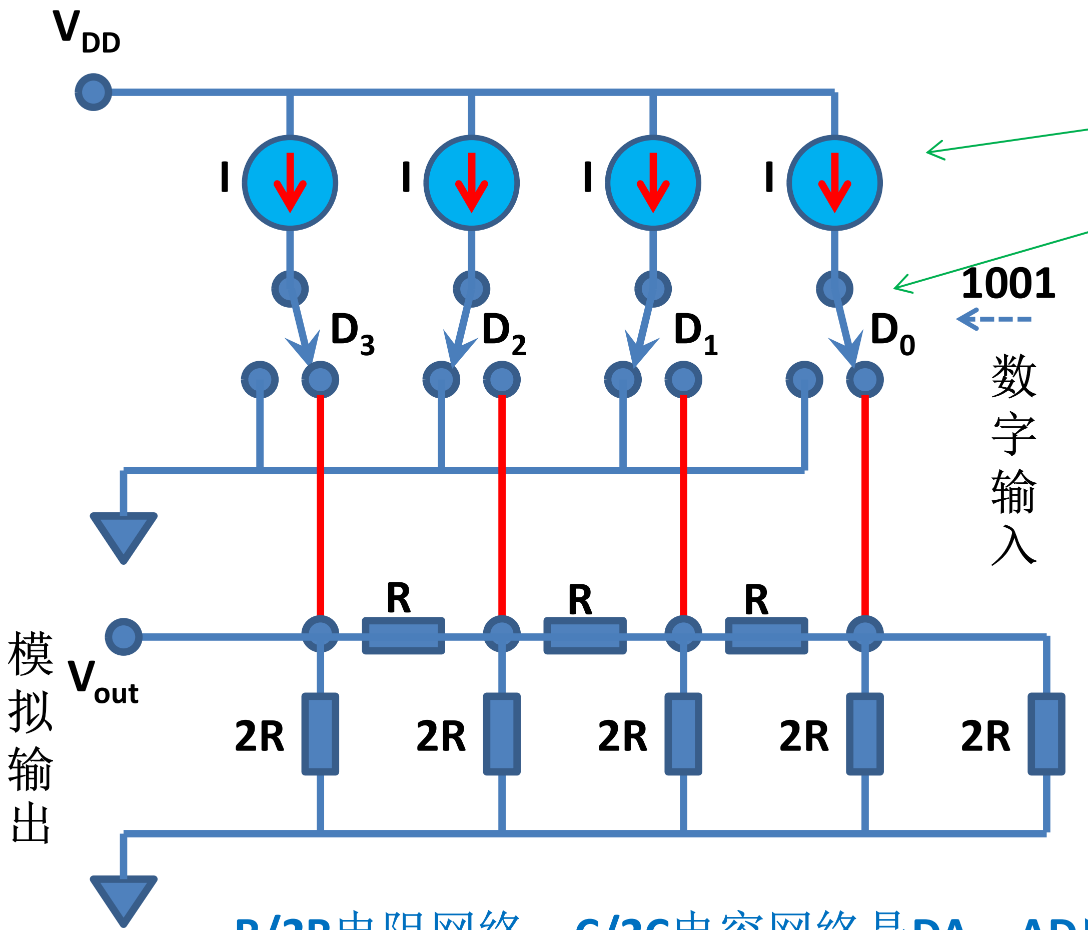
$$R_N = R$$

$$i_N = D_2 I + \frac{1}{2} \left(D_1 I + \frac{1}{2} D_0 I \right)$$

$$R_N = R$$

$$i_N = D_3 I + \frac{1}{2} \left(D_2 I + \frac{1}{2} \left(D_1 I + \frac{1}{2} D_0 I \right) \right)$$

为何这种结构？就是实际可实现结构

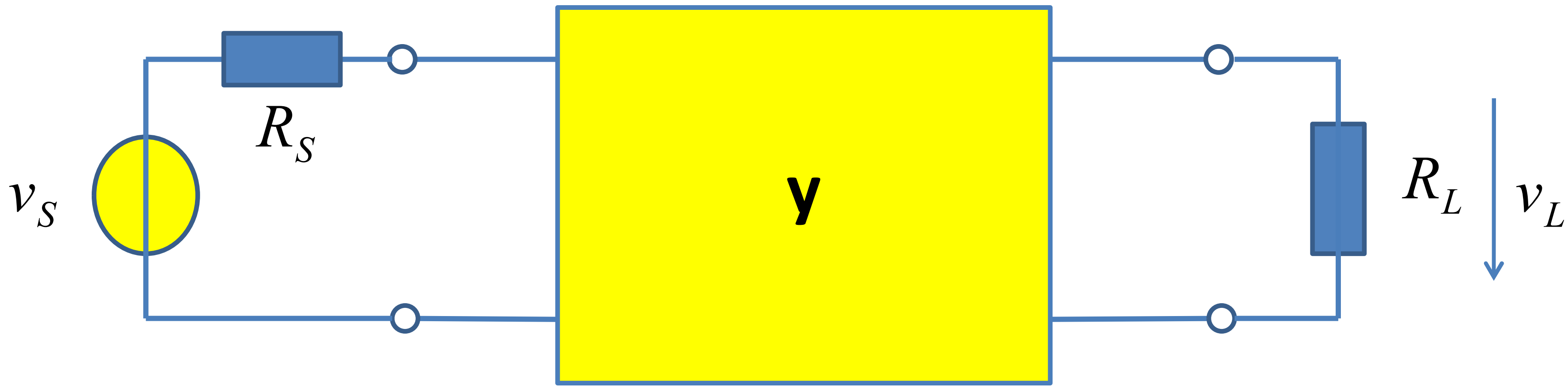


电流源和开关均可由晶体管在直流偏置电压源的偏置下得以实现

第4章：晶体管

R/2R电阻网络、C/2C电容网络是DA、AD电路的常见结构

第6周作业 作业3 单向化条件



$$H_{双向网络}=\frac{v_L}{v_S}=\frac{v_2}{v_S}=\frac{y_{21}G_S}{y_{21}y_{12}-(y_{11}+G_S)(y_{22}+G_L)}$$

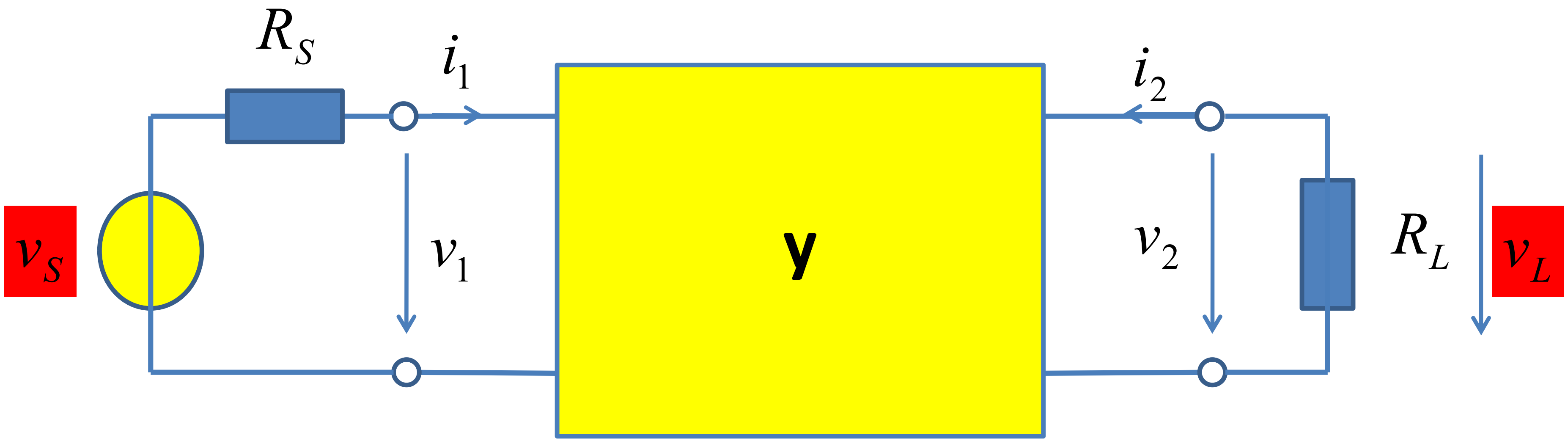
$$H_{单向网络}\overset{y_{12}=0}{=}\frac{y_{21}G_S}{-(y_{11}+G_S)(y_{22}+G_L)}$$

如果满足单向化条件： $|y_{21}y_{12}| \ll |(y_{11}+G_S)(y_{22}+G_L)|$

双向网络则可等视为单向网络 $H_{双向网络}\approx H_{单向网络}$

给出用z参量、h参量、g参量表述的线性二端口网络的单向化条件

y参量表述下的电压传递函数



$$y_{11}v_1 + y_{12}v_2 - i_1 = 0 \qquad v_1 + R_S i_1 = v_S$$

$$y_{21}v_1 + y_{22}v_2 - i_2 = 0 \qquad v_2 + R_L i_2 = 0$$

课堂上用电路语言分析，下面纯由数学语言进行分析

$$y_{11}v_1 + y_{12}v_2 - i_1 = 0$$

$$y_{21}v_1 + y_{22}v_2 - i_2 = 0$$

$$v_1 + R_S i_1 = v_S$$

$$v_2 + R_L i_2 = 0$$

v2是感兴趣量，所有变量用v2表述

$$i_2 = -G_L v_2$$

$$y_{21}v_1 + y_{22}v_2 + G_L v_2 = 0$$

$$v_1 = -\frac{y_{22} + G_L}{y_{21}} v_2$$

$$-\frac{y_{22} + G_L}{y_{21}} v_2 + R_S\left(y_{12} - y_{11}\frac{y_{22} + G_L}{y_{21}}\right) v_2 = v_S$$

$$-y_{11}\frac{y_{22} + G_L}{y_{21}} v_2 + y_{12}v_2 - i_1 = 0$$

$$i_1 = \left(y_{12} - y_{11}\frac{y_{22} + G_L}{y_{21}}\right) v_2$$

基于y参量的电压传递函数

$$-\frac{y_{22}+G_L}{y_{21}}v_2+R_S\left(y_{12}-y_{11}\frac{y_{22}+G_L}{y_{21}}\right)v_2=v_S$$

$$-G_S(y_{22}+G_L)v_2+(y_{12}y_{21}-y_{11}(y_{22}+G_L))v_2=G_Sy_{21}v_S$$

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

不如等效电路物理意义清晰，电路语言更容易查错纠错，建议多采用电路语言

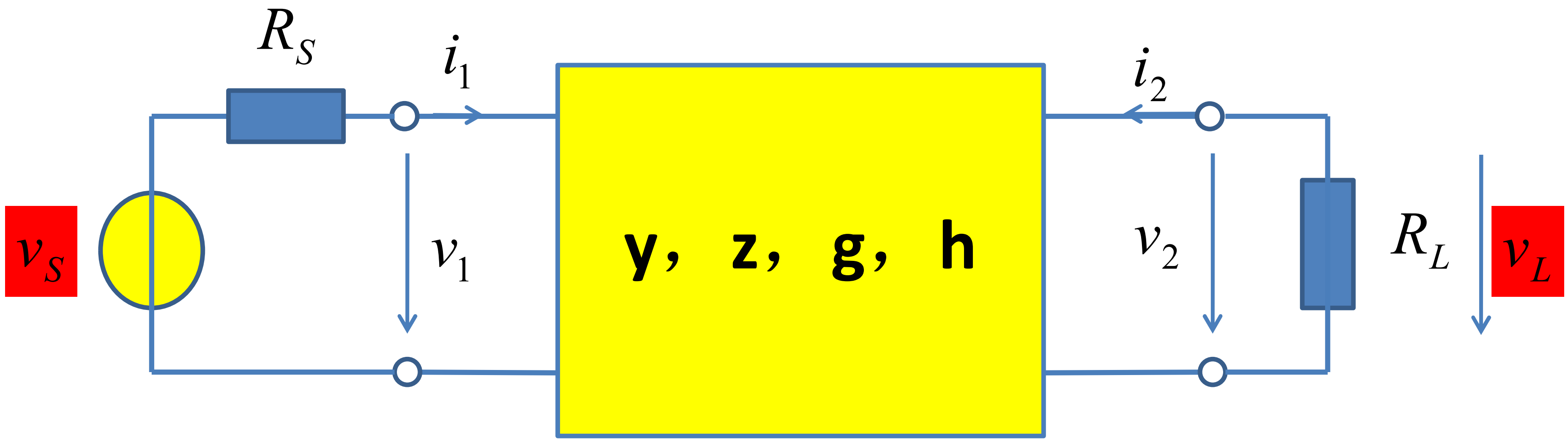
单向化条件： $|y_{12}y_{21}|<<|(y_{11}+G_S)(y_{22}+G_L)|$

$$H=\frac{v_L}{v_S}\approx\frac{1}{y_{22}+G_L}(-y_{21})\frac{G_S}{G_S+y_{11}}\sim\frac{R_LR_{out}}{R_L+R_{out}}(G_{m0})\frac{R_{in}}{R_S+R_{in}}$$

单向化条件满足，
则近似视为单向网络

$$\sim\frac{G_L}{G_L+G_{out}}(G_{m0}R_L)\frac{R_{in}}{R_S+R_{in}}$$

$$G_{m0}=-y_{21},R_{in}\approx\frac{1}{y_{11}},G_{out}\approx y_{22}$$



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

单向化条件满足，则可近似视为单向网络

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

$$H=\frac{v_L}{v_S}=-\frac{R_L z_{21}}{z_{12}z_{21}-(z_{11}+R_S)(z_{22}+R_L)}$$

$$|z_{12}z_{21}| << |(z_{11}+R_S)(z_{22}+R_L)|$$

$$H=\frac{v_L}{v_S}=\frac{h_{21}}{h_{12}h_{21}-(h_{11}+R_S)(h_{22}+G_L)}$$

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

$$H=\frac{v_L}{v_S}=-\frac{g_{21}R_L G_S}{g_{12}g_{21}-(g_{11}+G_S)(g_{22}+R_L)}$$

$$|g_{12}g_{21}| << |(g_{11}+G_S)(g_{22}+R_L)|$$

近似视为单向网络

$$H \approx \frac{G_S y_{21}}{-(y_{11}+G_S)(y_{22}+G_L)} = \frac{R_L R_{out}}{R_L+R_{out}} G_{m0} \frac{R_{in}}{R_S+R_{in}}$$

输出回路流压转换　理想跨导器跨导增益　输入回路分压系数

$$H \approx \frac{R_L z_{21}}{(z_{11}+R_S)(z_{22}+R_L)} = \frac{R_L}{R_{out}+R_L} R_{m0} \frac{1}{R_{in}+R_S}$$

输出回路分压系数　理想跨阻器跨阻增益　输入回路压流转换

$$H \approx \frac{h_{21}}{-(h_{11}+R_S)(h_{22}+G_L)} = \frac{R_{out} R_L}{R_{out}+R_L} A_{i0} \frac{1}{R_{in}+R_S}$$

输出回路流压转换　理想电流放大电流增益　输入回路压流转换

$$H \approx \frac{g_{21} R_L G_S}{(g_{11}+G_S)(g_{22}+R_L)} = \frac{R_L}{R_{out}+R_L} A_{v0} \frac{R_{in}}{R_{in}+R_S}$$

输出回路分压系数　理想电压放大电压增益　输入回路分压系数

强烈反向作用对正向传输的影响

$$H=\frac{v_L}{v_S}=\frac{G_S y_{21}}{y_{12}y_{21}-(y_{11}+G_S)(y_{22}+G_L)}\approx\frac{G_S}{y_{12}}=\frac{1}{R_S}R_{mf}$$

跨导反馈系数　　闭环跨阻增益

$$H=\frac{v_L}{v_S}=-\frac{R_L z_{21}}{z_{12}z_{21}-(z_{11}+R_S)(z_{22}+R_L)}\approx-\frac{R_L}{z_{12}}=-G_{mf}R_L$$

跨阻反馈系数　　闭环跨导增益

$$H=\frac{v_L}{v_S}=\frac{h_{21}}{h_{12}h_{21}-(h_{11}+R_S)(h_{22}+G_L)}\approx\frac{1}{h_{12}}=A_{vf}$$

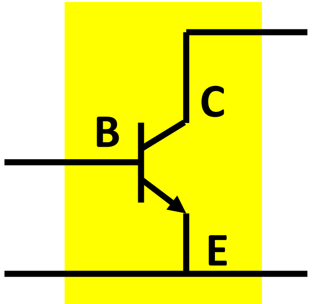
电压反馈系数　　闭环电压增益

$$H=\frac{v_L}{v_S}=-\frac{g_{21}R_L G_S}{g_{12}g_{21}-(g_{11}+G_S)(g_{22}+R_L)}\approx-\frac{R_L G_S}{g_{12}}=-\frac{1}{R_S}A_{if}R_L$$

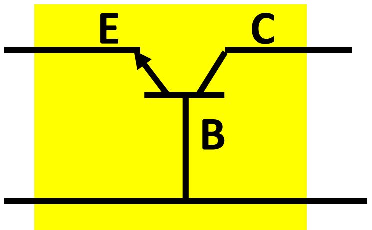
电流反馈系数　　闭环电流增益

强烈的双向作用，甚至可导致反向作用系数决定整个网络的传输特性

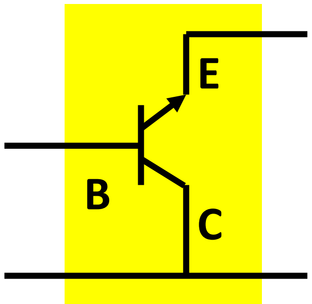
深度负反馈放大：利用负反馈网络提供稳定的反向作用系数（反馈系数），放大器放大倍数由稳定的负反馈网络决定，大体等于反馈系数的倒数



Common Emitter

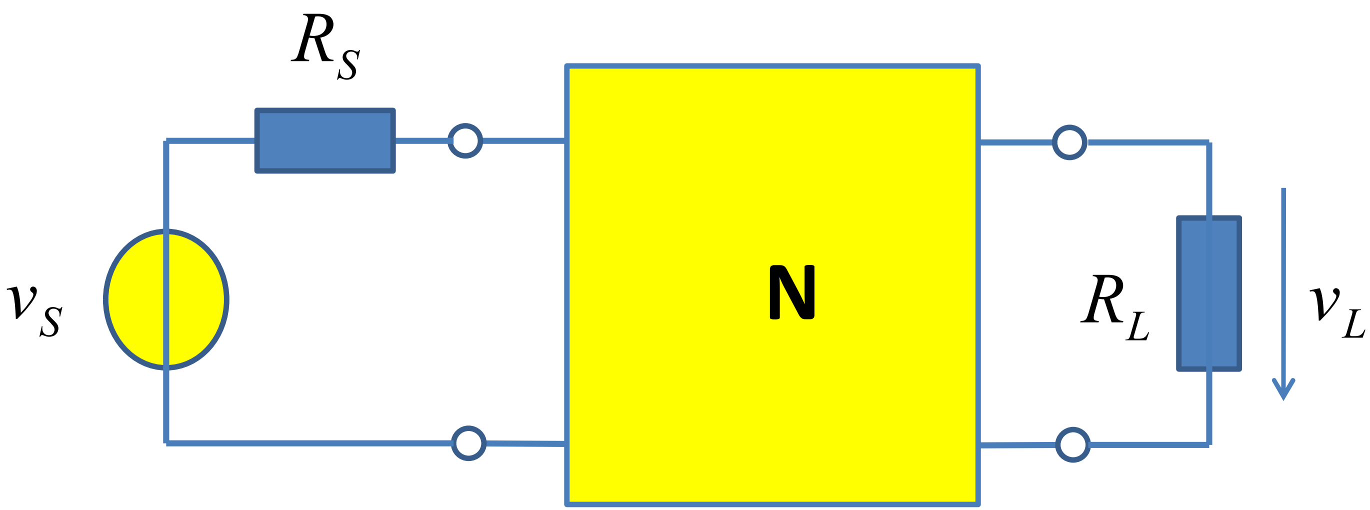


Common Base



Common Collector

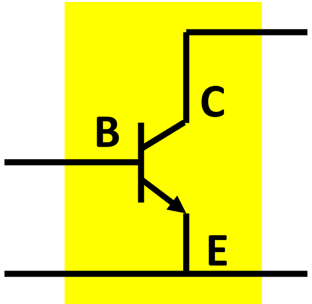
作业4 求电压放大倍数



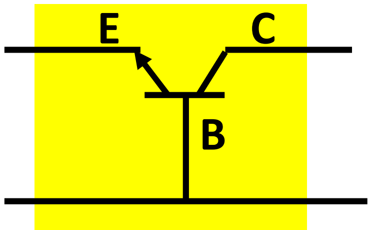
求三种组态晶体管放大器的输入电阻，输出电阻，电压传递函数表达式（符号表达式），代入具体数值求其电压放大倍数（R_S=50Ω,R_L=1kΩ ）

方法不限：可以用回路电流法，结点电压法，二端口网络参量法

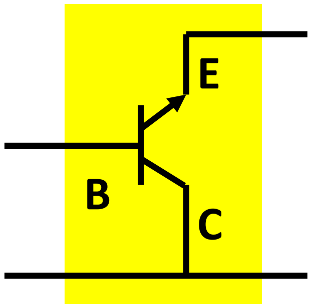
BJT 交流小信号电路模型



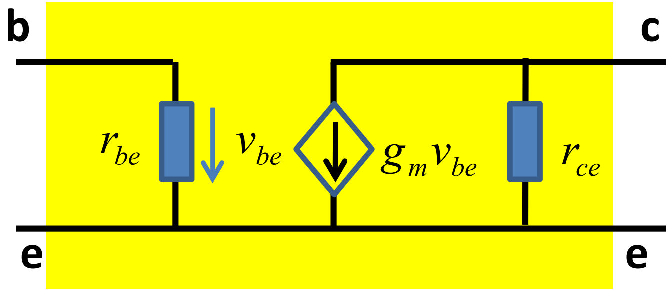
Common Emitter



Common Base



Common Collector

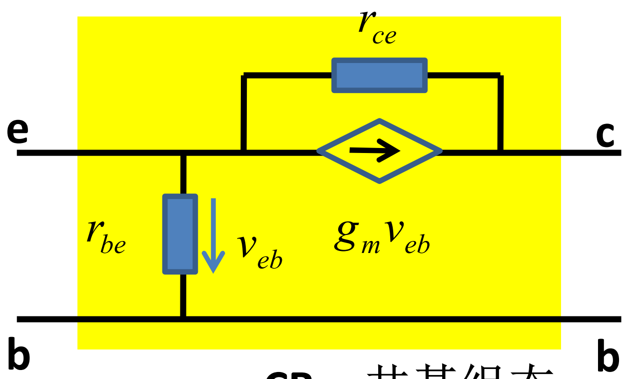


$g_m = 40mS$

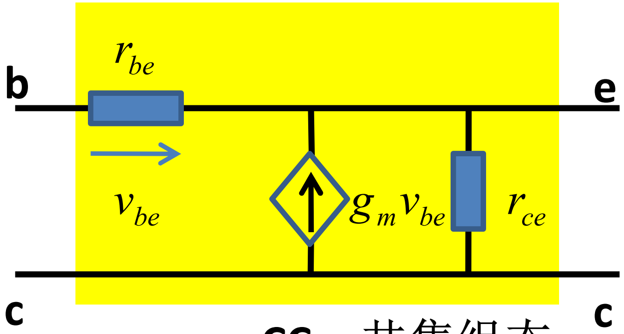
$r_{be} = 10k\Omega$

$r_{ce} = 100k\Omega$

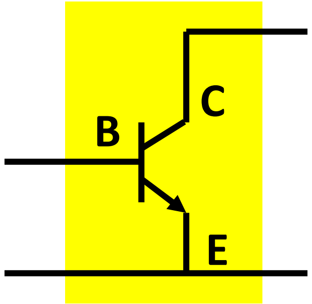
CE：共射组态



CB：共基组态

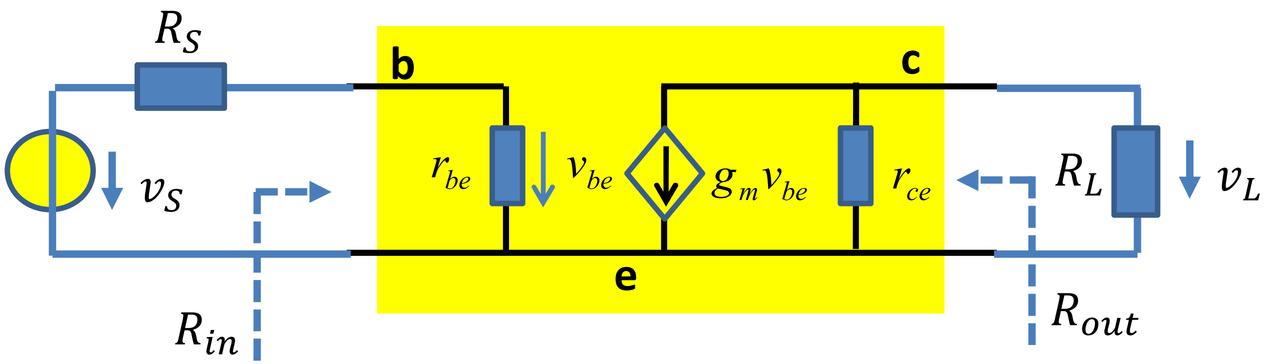


CC：共集组态



Common Emitter

CE组态晶体管放大器



$$R_{in} = r_{be} = \mathbf{10k\Omega}$$

$$R_{out} = r_{ce} = \mathbf{100k\Omega}$$

单向网络

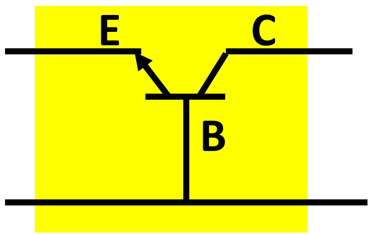
$$H = A_v = \frac{r_{ce}R_L}{r_{ce} + R_L}(-g_m)\frac{r_{be}}{r_{be} + R_S}$$

输出回路总电阻 本征跨导增益 输入回路分压系数

$$= (100k\Omega||1k\Omega) \times (-40mS) \times \frac{10k\Omega}{10k\Omega + 50\Omega}$$

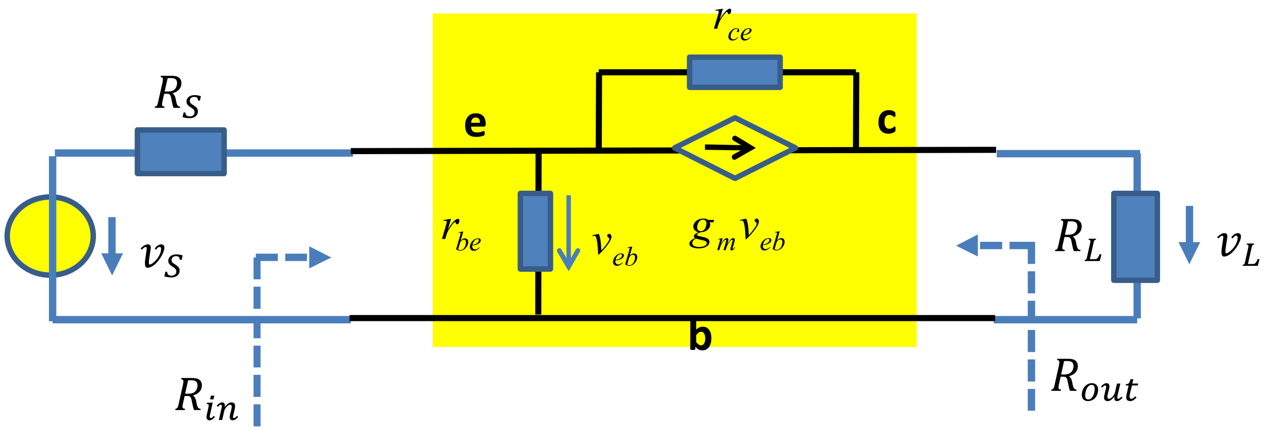
$$= 990\Omega \times (-40mS) \times 0.995$$

$$= -39.4 = 31.9dB$$ 反相电压放大

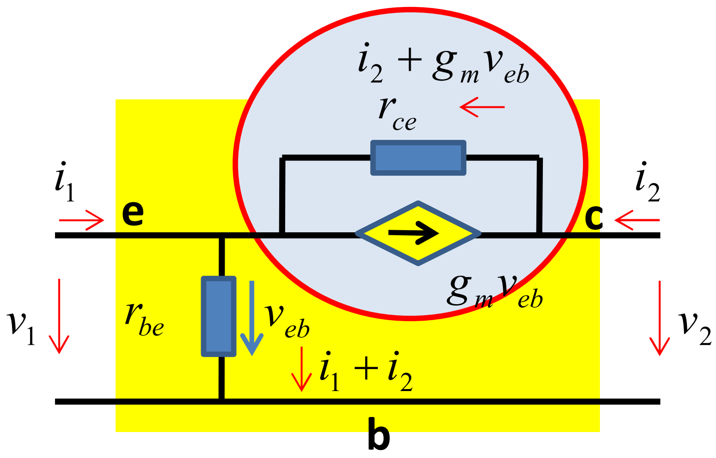


CB组态晶体管放大器

Common Base



回路电流法、结点电压法自行练习，本节重点考察网络参量法

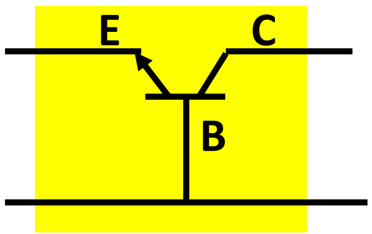


$$v_1 = (i_1 + i_2) r_{be} = r_{be} i_1 + r_{be} i_2$$

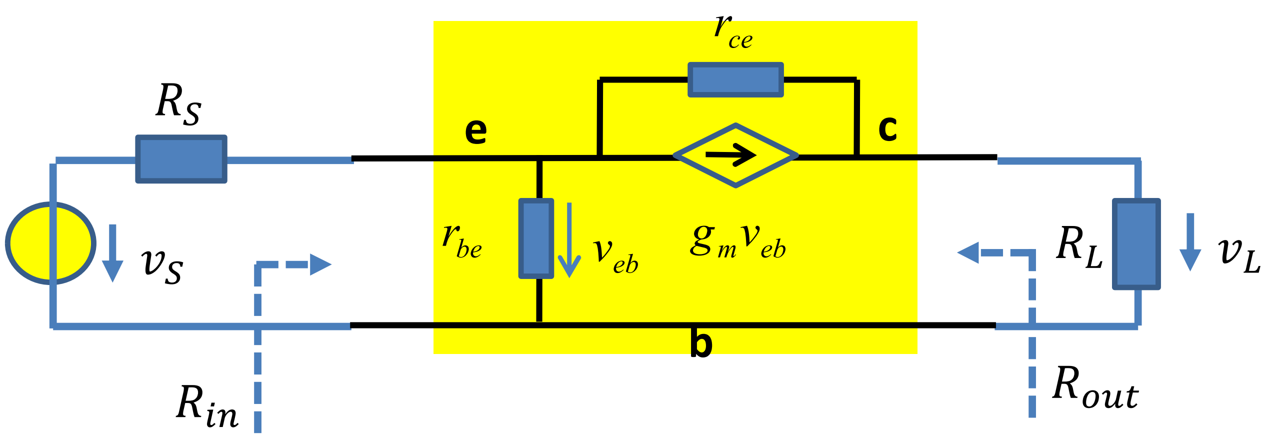
$$v_2 = (i_2 + g_m v_{eb}) r_{ce} + v_{eb} = i_2 r_{ce} + (g_m r_{ce} + 1) v_1$$

$$= (g_m r_{ce} + 1) r_{be} i_1 + (g_m r_{be} r_{ce} + r_{be} + r_{ce}) i_2$$

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



Common Base



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

$$R_{in} = z_{in} = z_{11} - \frac{z_{12} z_{21}}{z_{22} + R_L} = r_{be} - \frac{r_{be}(g_m r_{ce} + 1) r_{be}}{g_m r_{be} r_{ce} + r_{be} + r_{ce} + R_L} = \frac{(r_{ce} + R_L) r_{be}}{g_m r_{be} r_{ce} + r_{be} + r_{ce} + R_L}$$

$$= \frac{(r_{ce} + R_L) r_{be}}{r_{be}(g_m r_{ce} + 1) + r_{ce} + R_L} = \frac{\frac{r_{ce} + R_L}{1 + g_m r_{ce}} r_{be}}{r_{be} + \frac{r_{ce} + R_L}{1 + g_m r_{ce}}} = r_{be} || \frac{r_{ce} + R_L}{1 + g_m r_{ce}} = \mathbf{10k} || 25.24 = \mathbf{25.18\Omega}$$

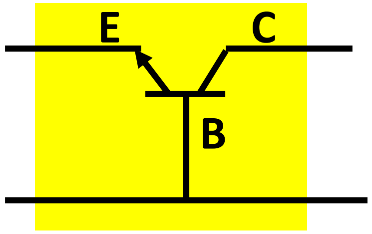
发射极对地阻抗

$$R_{out} = z_{out} = z_{22} - \frac{z_{21} z_{12}}{z_{11} + R_S} = g_m r_{be} r_{ce} + r_{be} + r_{ce} - \frac{r_{be}(g_m r_{ce} + 1) r_{be}}{r_{be} + R_S}$$

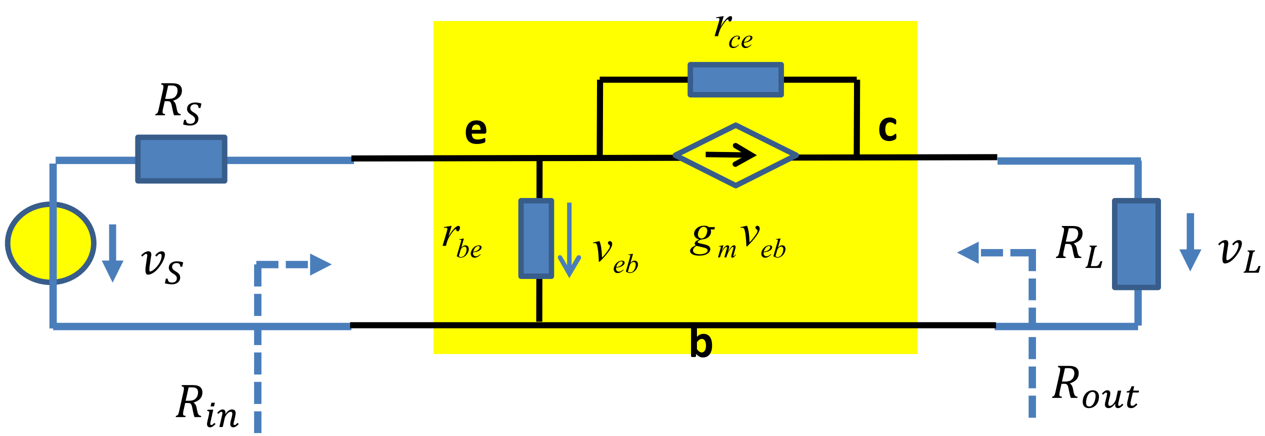
bc端口阻抗

$$= g_m r_{be} r_{ce} \left(1 - \frac{r_{be}}{r_{be} + R_S}\right) + r_{be}\left(1 - \frac{r_{be}}{r_{be} + R_S}\right) + r_{ce} = g_m (r_{be} || R_S) r_{ce} + r_{be} || R_S + r_{ce}$$

$$= \mathbf{199k + 49.75 + 100k = 299.05k\Omega}$$



Common Base



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

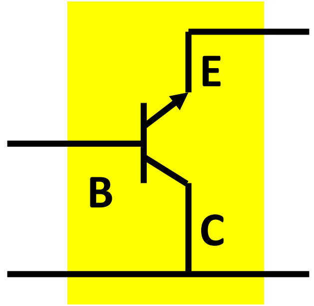
$$H = A_v = \frac{z_{21} R_L}{(z_{22} + R_L)(z_{11} + R_S) - z_{21} z_{12}}$$

$$= \frac{(g_m r_{ce} + 1) r_{be} R_L}{(g_m r_{be} r_{ce} + r_{be} + r_{ce} + R_L)(r_{be} + R_S) - r_{be}(g_m r_{ce} + 1) r_{be}}$$

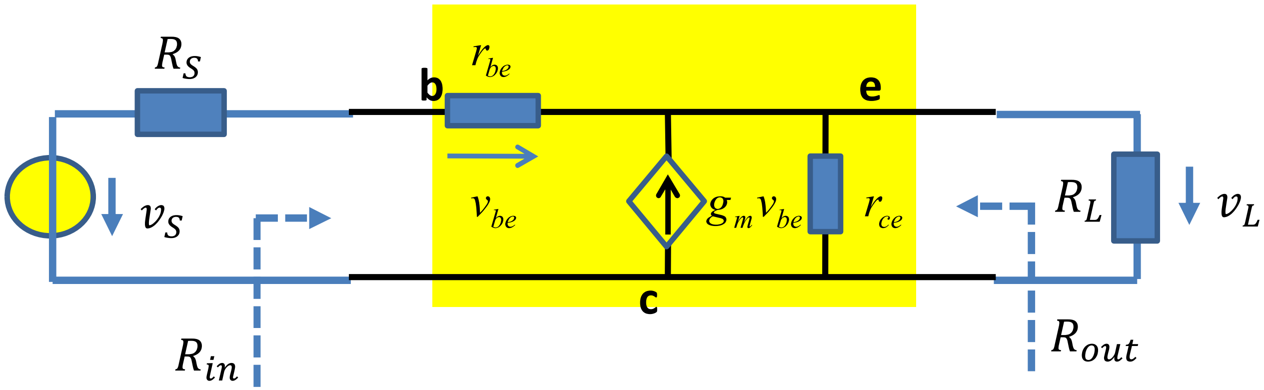
$$= \frac{(g_m r_{ce} + 1) r_{be} R_L}{(g_m r_{ce} + 1) r_{be} R_S + (r_{be} + R_S)(r_{ce} + R_L)}$$

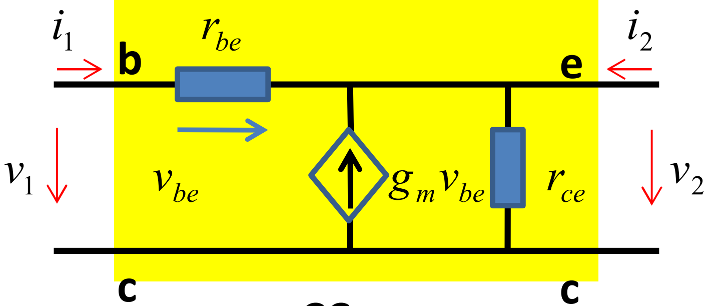
$= \mathbf{13.27} = \mathbf{22.46}\boldsymbol{dB}$同相电压放大

CC组态晶体管放大器



Common Collector



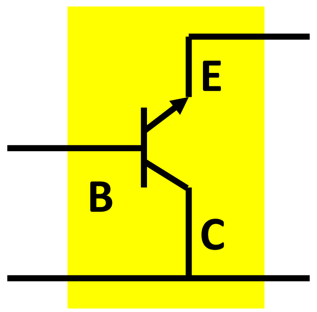


CC

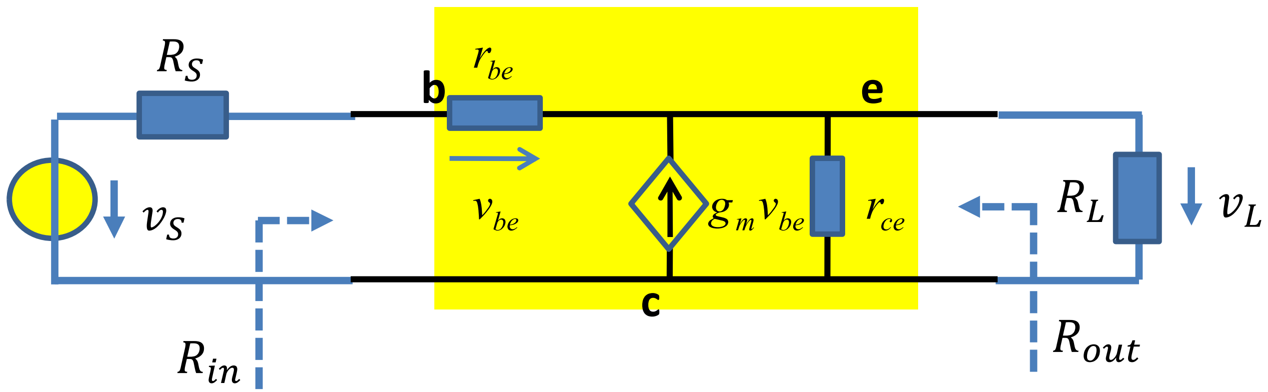
$$v_2 = r_{ce}(i_2 + i_1 + g_m v_{be}) = r_{ce}(i_2 + i_1 + g_m r_{be} i_1)$$
$$= (1 + g_m r_{be}) r_{ce} i_1 + r_{ce} i_2$$

$$v_1 = i_1 r_{be} + v_2 = (r_{be} + r_{ce} + g_m r_{be} r_{ce}) i_1 + r_{ce} i_2$$

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



Common Collector



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

$$R_{in} = z_{in} = z_{11} - \frac{z_{12} z_{21}}{z_{22} + R_L} = g_m r_{be} r_{ce} + r_{be} + r_{ce} - \frac{r_{ce}(g_m r_{be} + 1) r_{ce}}{r_{ce} + R_L}$$

bc端口阻抗

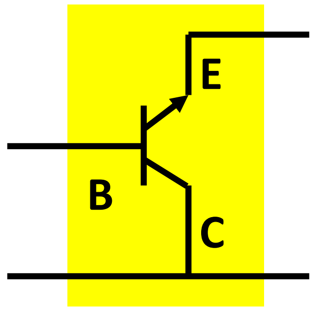
$$= g_m r_{be} r_{ce}\left(1 - \frac{r_{ce}}{r_{ce} + R_L}\right) + r_{be} + r_{ce}\left(1 - \frac{r_{ce}}{r_{ce} + R_L}\right) = g_m r_{be}(r_{ce}||R_L) + r_{be} + r_{ce}||R_L$$

$$= 396\boldsymbol{k} + 10\text{k} + 990 = \boldsymbol{407k\Omega}$$

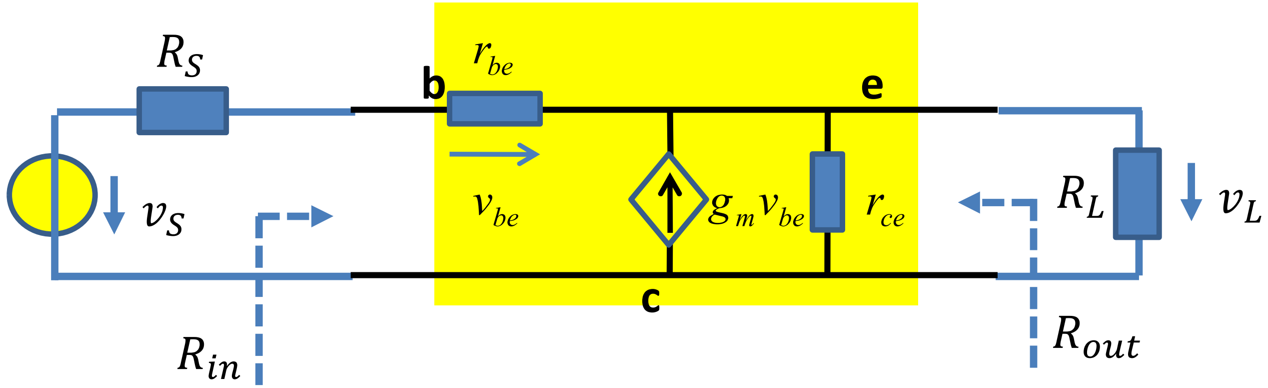
$$R_{out} = z_{out} = z_{22} - \frac{z_{21} z_{12}}{z_{11} + R_S} = r_{ce} - \frac{r_{ce}(g_m r_{be} + 1) r_{ce}}{g_m r_{be} r_{ce} + r_{be} + r_{ce} + R_S} = \frac{(r_{be} + R_S) r_{ce}}{g_m r_{be} r_{ce} + r_{be} + r_{ce} + R_S}$$

$$= \frac{(r_{be} + R_S) r_{ce}}{r_{ce}(g_m r_{be} + 1) + r_{be} + R_S} = \frac{\frac{r_{be} + R_S}{1 + g_m r_{be}} r_{ce}}{r_{ce} + \frac{r_{be} + R_S}{1 + g_m r_{be}}} = r_{ce}||\frac{r_{be} + R_S}{1 + g_m r_{be}} = \boldsymbol{100k}||25.06 = \boldsymbol{25.06\Omega}$$

发射极对地阻抗



Common Collector



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

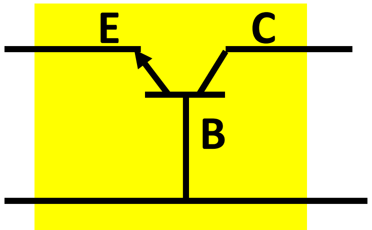
$$H = A_v = \frac{z_{21} R_L}{(z_{22} + R_L)(z_{11} + R_S) - z_{21} z_{12}}$$

$$= \frac{(g_m r_{be} + 1) r_{ce} R_L}{(r_{ce} + R_L)(g_m r_{be} r_{ce} + r_{be} + r_{ce} + R_S) - r_{ce}(g_m r_{be} + 1) r_{ce}}$$

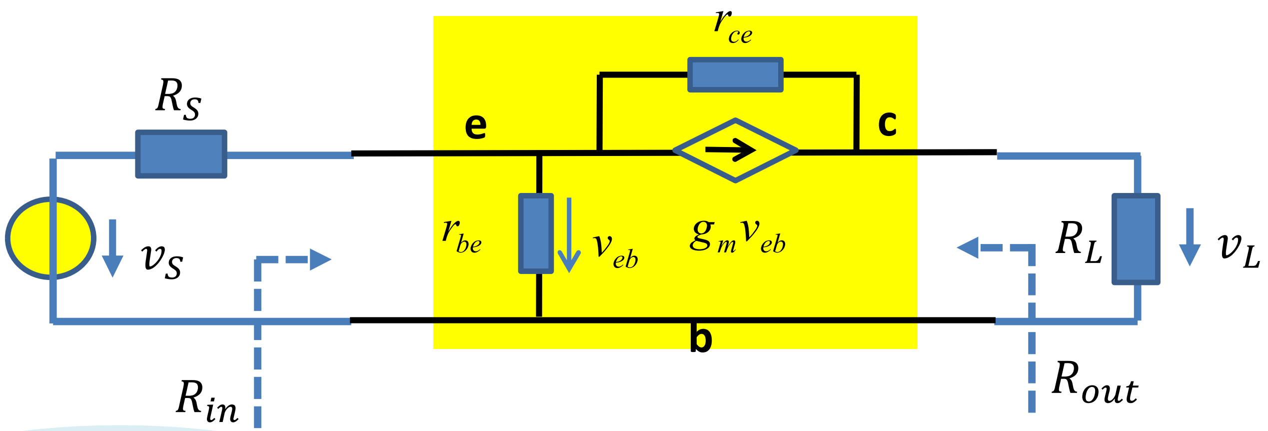
$$= \frac{(g_m r_{be} + 1) r_{ce} R_L}{(g_m r_{be} + 1) r_{ce} R_L + (r_{be} + R_S)(r_{ce} + R_L)}$$

$= \mathbf{0.9753} = -\mathbf{0.22}\boldsymbol{dB}$电压缓冲？（电压增益近似为1）

输入阻抗和输出阻抗中的异同



Common Base



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

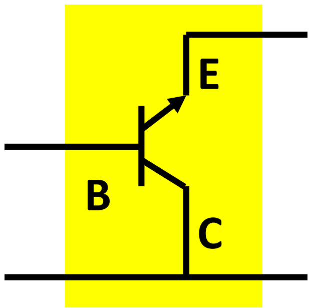
$$= 25.18\Omega$$

发射极对地阻抗

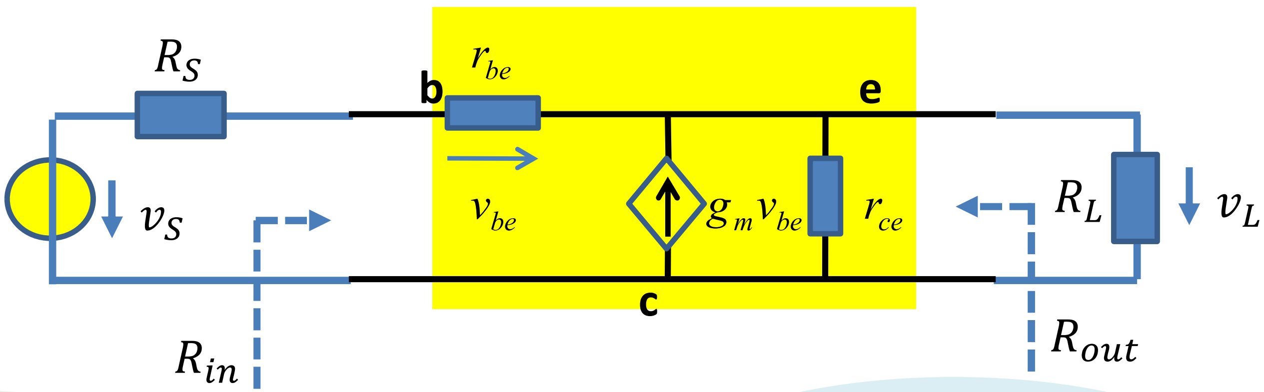
$$R_{out} = g_m(r_{be}||R_S)r_{ce} + r_{be}||R_S + r_{ce}$$

$$= 299k\Omega$$

bc端口阻抗



Common Collector



$$R_{in} = g_m r_{be}(r_{ce}||R_L) + r_{be} + r_{ce}||R_L$$

$$= 407k\Omega$$

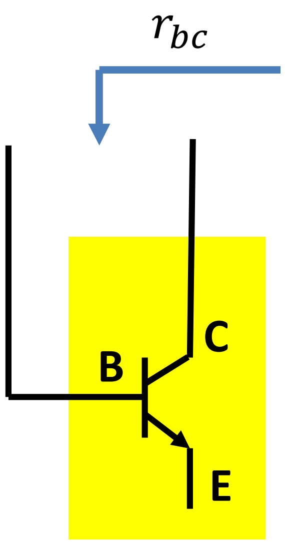
bc端口阻抗

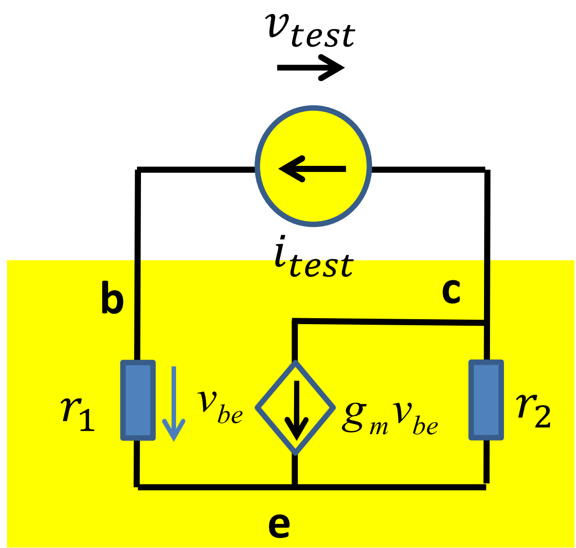
$$R_{out} = r_{ce} || \frac{r_{be} + R_S}{1 + g_m r_{be}}$$

$$= 25.06\Omega$$

发射极对地阻抗

bc阻抗

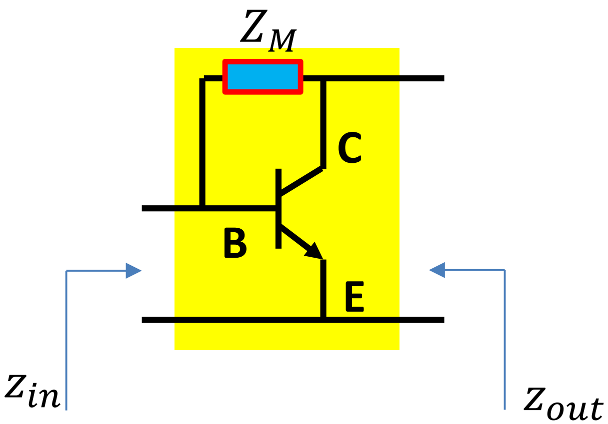


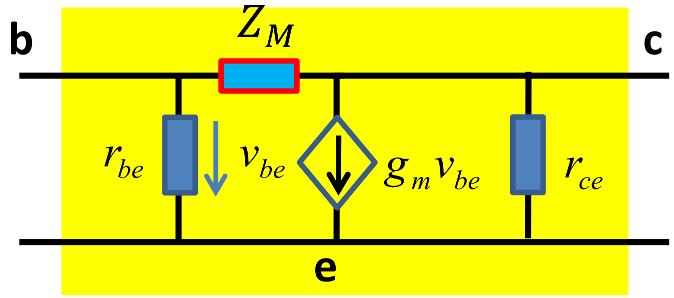


$$
\begin{aligned}
v_{test} &= i_{test} r_1 + (i_{test} + g_m v_{be}) r_2 \\
&= i_{test} r_1 + (i_{test} + g_m i_{test} r_1) r_2
\end{aligned}
$$

$$
r_{bc} = \frac{v_{test}}{i_{test}} = r_1 + (1 + g_m r_1) r_2 = g_m r_1 r_2 + r_1 + r_2
$$

MILLER效应阻抗





$$\boldsymbol{y} = \begin{bmatrix} g_{be} & 0 \\ g_m & g_{ce} \end{bmatrix} + \begin{bmatrix} Y_M & -Y_M \\ -Y_M & Y_M \end{bmatrix} = \begin{bmatrix} g_{be} + Y_M & -Y_M \\ g_m - Y_M & g_{ce} + Y_M \end{bmatrix}$$

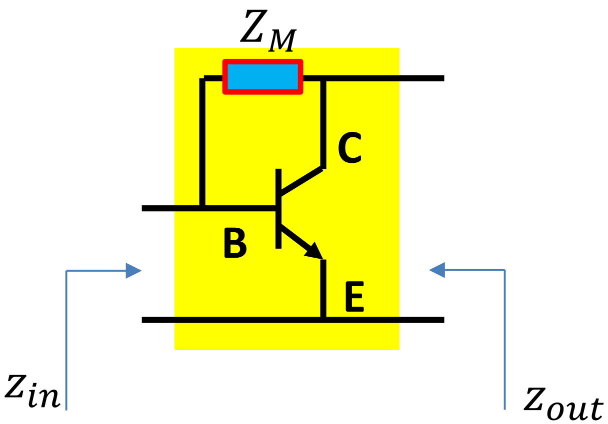
$$\boldsymbol{z} = \boldsymbol{y}^{-1} = \frac{\begin{bmatrix} g_{ce} + Y_M & Y_M \\ -g_m + Y_M & g_{be} + Y_M \end{bmatrix}}{(g_{be} + Y_M)(g_{ce} + Y_M) + Y_M(g_m - Y_M)} = \frac{\begin{bmatrix} g_{ce} + Y_M & Y_M \\ -g_m + Y_M & g_{be} + Y_M \end{bmatrix}}{g_{be}g_{ce} + Y_M(g_m + g_{be} + g_{ce})}$$

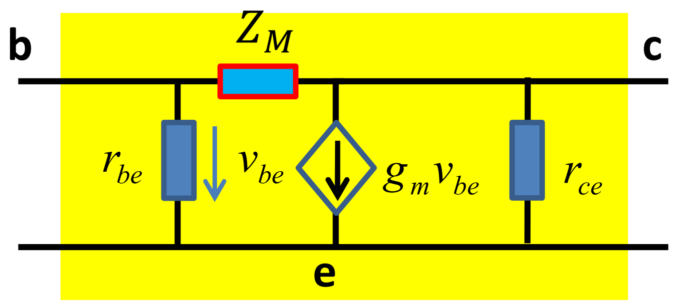
$$z_{in} = z_{11} = \frac{g_{ce} + Y_M}{g_{be}g_{ce} + Y_M(g_m + g_{be} + g_{ce})} = \frac{r_{ce} + Z_M}{g_{be}Z_M + r_{ce}(g_m + g_{be} + g_{ce})}$$

$$= \frac{r_{ce} + Z_M}{g_{be}(r_{ce} + Z_M) + (g_m r_{ce} + 1)} = \frac{\frac{r_{ce} + Z_M}{g_m r_{ce} + 1}}{g_{be}\frac{r_{ce} + Z_M}{g_m r_{ce} + 1} + 1} = \frac{\frac{r_{ce} + Z_M}{g_m r_{ce} + 1} r_{be}}{\frac{r_{ce} + Z_M}{g_m r_{ce} + 1} + r_{be}} = r_{be} || \frac{r_{ce} + Z_M}{g_m r_{ce} + 1}$$

$$z_{out} = z_{22} = \frac{g_{be} + Y_M}{g_{be}g_{ce} + Y_M(g_m + g_{be} + g_{ce})} = \cdots = r_{ce} || \frac{r_{be} + Z_M}{g_m r_{be} + 1}$$

MILLER效应阻抗





$$z_{in} = r_{be}||\frac{r_{ce}+Z_M}{g_m r_{ce}+1} \overset{Z_M \ll r_{ce}}{\approx} r_{be}||\frac{r_{ce}}{g_m r_{ce}+1} = r_{be}||r_{ce}||\frac{1}{g_m} \approx \frac{1}{g_m}$$

$$= 25\Omega$$

$$z_{out} = r_{ce}||\frac{r_{be}+Z_M}{g_m r_{be}+1} \overset{Z_M \ll r_{be}}{\approx} r_{ce}||\frac{r_{be}}{g_m r_{be}+1} = r_{ce}||r_{be}||\frac{1}{g_m} \approx \frac{1}{g_m}$$

$$z_{in} = r_{be}||\frac{r_{ce}+Z_M}{g_m r_{ce}+1} = r_{be}||\left(\frac{r_{ce}}{g_m r_{ce}+1}+\frac{Z_M}{g_m r_{ce}+1}\right) = r_{be}||\left(|r_{ce}||\frac{1}{g_m}+\frac{Z_M}{g_m r_{ce}+1}\right)$$

$$z_{out} = r_{ce}||\frac{r_{be}+Z_M}{g_m r_{be}+1} = r_{ce}||\left(\frac{r_{be}}{g_m r_{be}+1}+\frac{Z_M}{g_m r_{be}+1}\right) = r_{ce}||\left(|r_{be}||\frac{1}{g_m}+\frac{Z_M}{g_m r_{be}+1}\right)$$

三种组态的增益异同

$$A_{v,CE} = \frac{r_{ce}R_L}{r_{ce}+R_L}(-g_m)\frac{r_{be}}{r_{be}+R_S} \approx -g_mR_L = -40$$

反相电压放大

$$A_{v,CB} = \frac{(g_mr_{ce}+1)r_{be}R_L}{(g_mr_{ce}+1)r_{be}R_S+(r_{be}+R_S)(r_{ce}+R_L)}$$

$$\approx \frac{g_mr_{ce}r_{be}R_L}{g_mr_{ce}r_{be}R_S+r_{be}r_{ce}} = \frac{g_m}{1+g_mR_S}R_L = 13.33$$

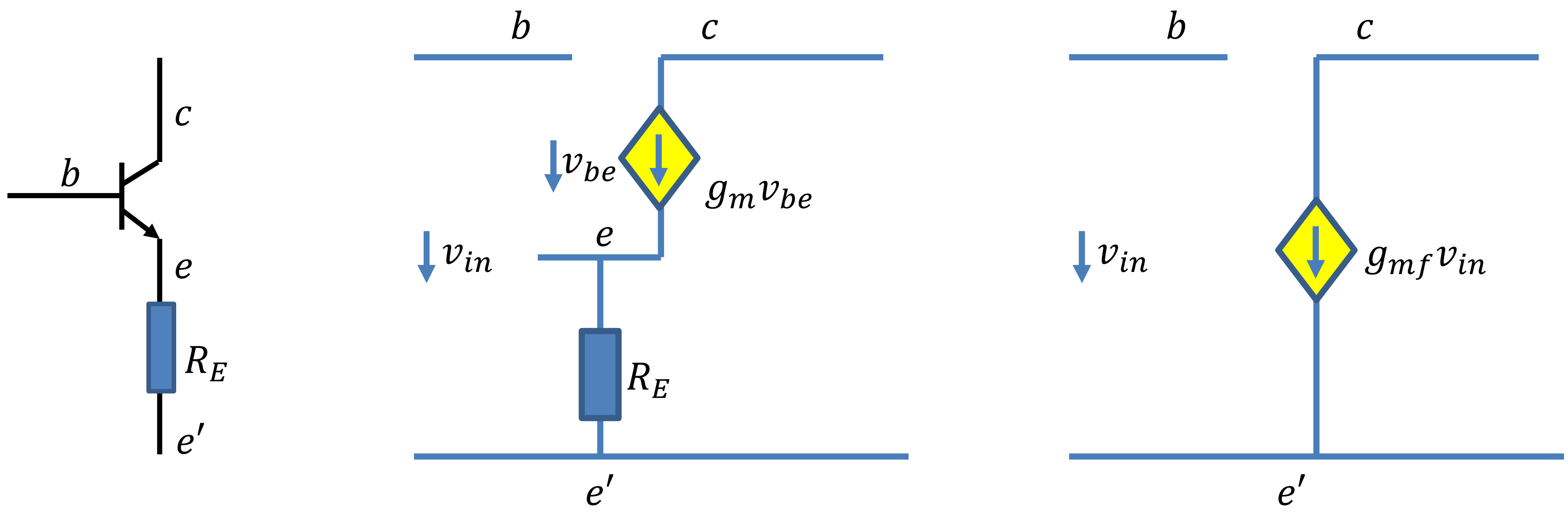
同相电压放大

$$A_{v,CC} = \frac{(g_mr_{be}+1)r_{ce}R_L}{(g_mr_{be}+1)r_{ce}R_L+(r_{be}+R_S)(r_{ce}+R_L)}$$

$$\approx \frac{g_mr_{be}r_{ce}R_L}{g_mr_{be}r_{ce}R_L+r_{be}r_{ce}} = \frac{g_m}{1+g_mR_L}R_L = 0.9756$$

同相电压放大

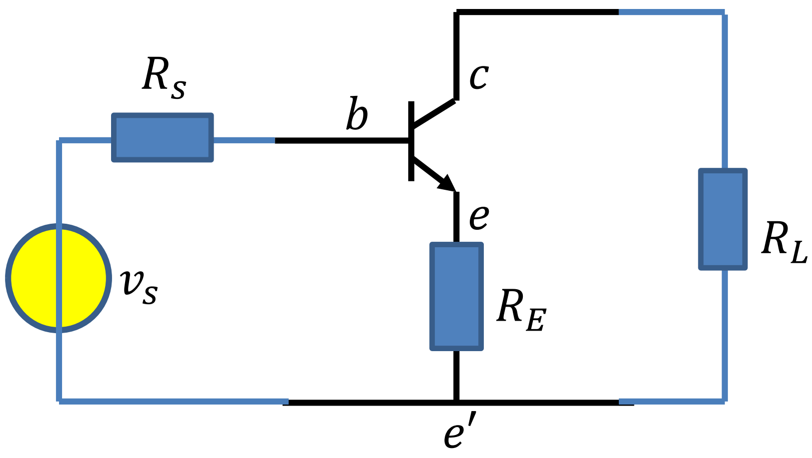
射极串联负反馈



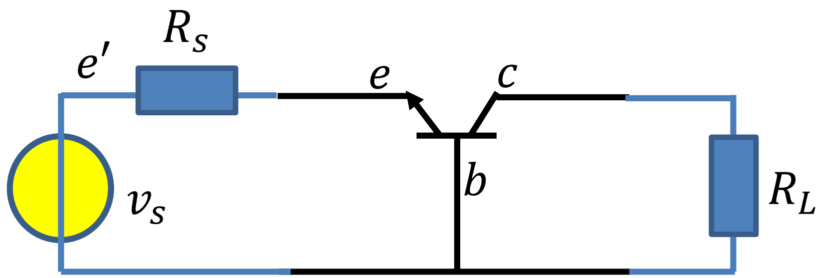
$$v_{in} = v_{be} + g_m v_{be} R_E = (1 + g_m R_E) v_{be}$$

$$i_c = g_m v_{be} = g_m \frac{1}{1 + g_m R_E} v_{in} = \frac{g_m}{1 + g_m R_E} v_{in} = g_{mf} v_{in}$$

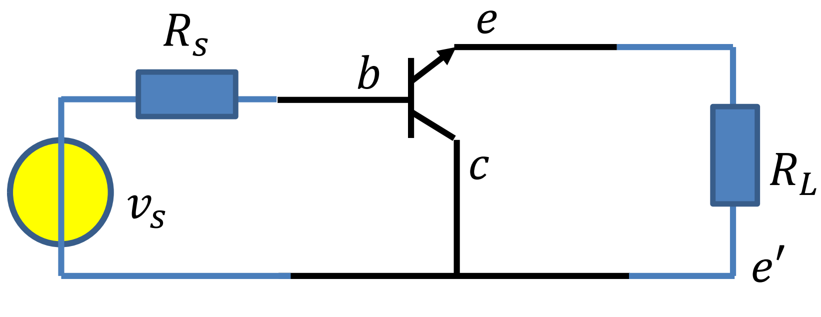
三种组态放大器放大倍数



$$A_{v,CE} = -g_{mf}R_L = -\frac{g_m}{1+g_mR_E}R_L$$

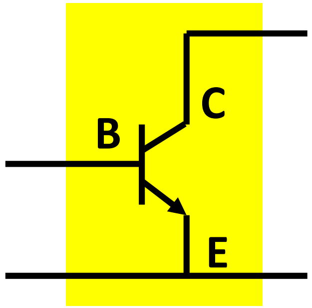


$$A_{v,CB} = g_{mf}R_L = \frac{g_m}{1+g_mR_S}R_L$$



$$A_{v,CC} = g_{mf}R_L = \frac{g_m}{1+g_mR_L}R_L$$

共射组态的简化原理性模型

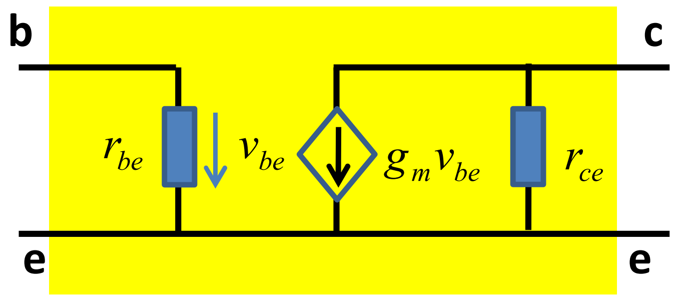


Common Emitter

$$g_m = 40mS$$

$$r_{be} = 10k\Omega$$

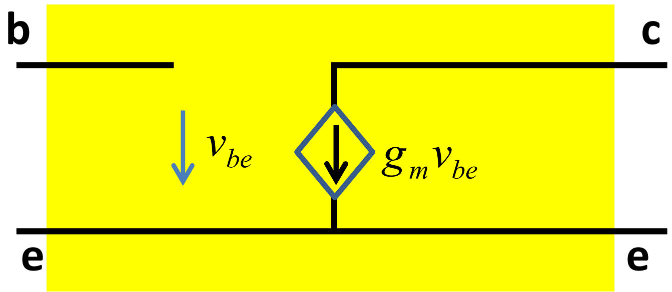
$$r_{ce} = 100k\Omega$$



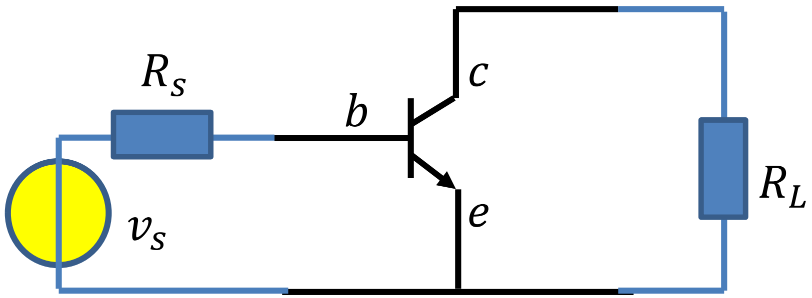
CE

$$\mathbf{y} = \begin{bmatrix} g_{be} & 0 \\ g_m & g_{ce} \end{bmatrix} = \begin{bmatrix} 0.1 & 0 \\ 40 & 0.01 \end{bmatrix} mS \approx \begin{bmatrix} 0 & 0 \\ 40 & 0 \end{bmatrix} mS$$

可采用的原理性模型：理想跨导器模型

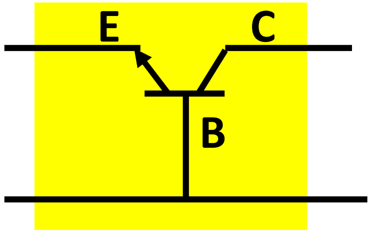


前提条件：$R_S \ll r_{be} = 10k\Omega$，$R_L \ll r_{ce} = 100k\Omega$

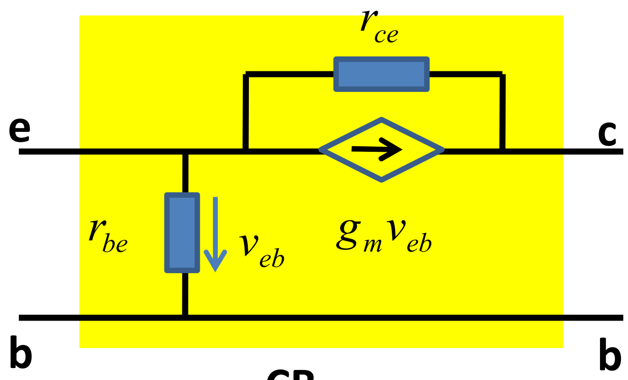


$$A_{v,CE} = -g_m R_L$$

共基组态的简化原理性模型



Common Base



CB

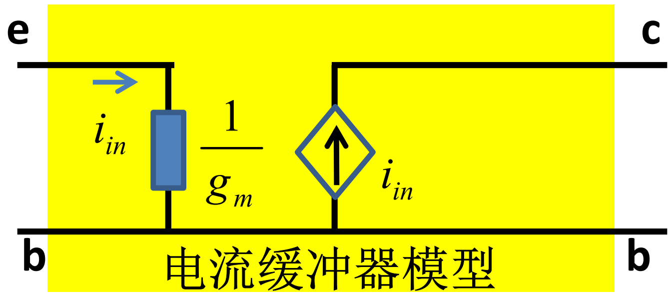
$$\mathbf{h}=\begin{bmatrix}\dfrac{1}{g_m+g_{be}+g_{ce}} & \dfrac{r_{be}}{g_m r_{be} r_{ce}+r_{be}+r_{ce}}\\ -\dfrac{g_m r_{be} r_{ce}+r_{be}}{g_m r_{be} r_{ce}+r_{be}+r_{ce}} & \dfrac{1}{g_m r_{be} r_{ce}+r_{be}+r_{ce}}\end{bmatrix}$$

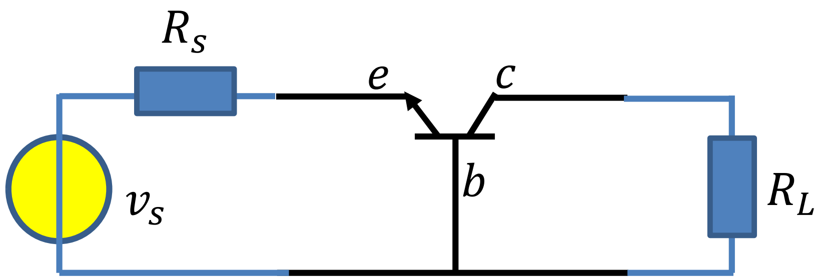
$$=\begin{bmatrix}24.9314\Omega & 0.0002493\\ -0.9975 & 0.02493\mu S\end{bmatrix}$$

$$\approx\begin{bmatrix}\dfrac{1}{g_m} & 0\\ -1 & 0\end{bmatrix}=\begin{bmatrix}25\Omega & 0\\ -1 & 0\end{bmatrix}$$

自行推导h参量矩阵
自行证明单向化条件

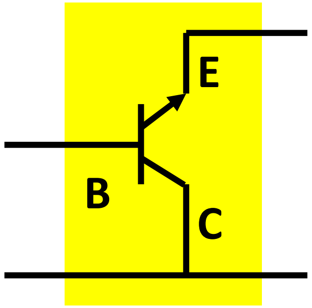
$R_L << r_{ce}=100k\Omega$



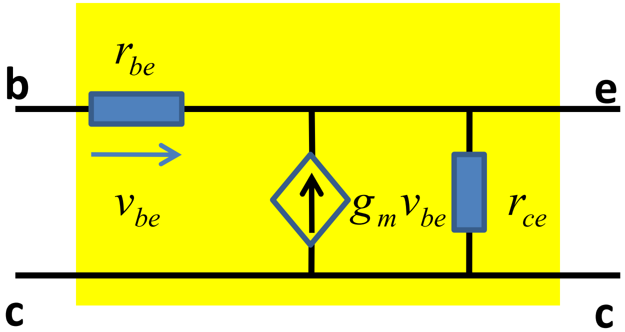


$$A_{v,CB}=R_L\frac{1}{R_S+\dfrac{1}{g_m}}=\frac{g_m}{1+g_m R_S}R_L$$

共集组态的简化原理性模型



Common Collector



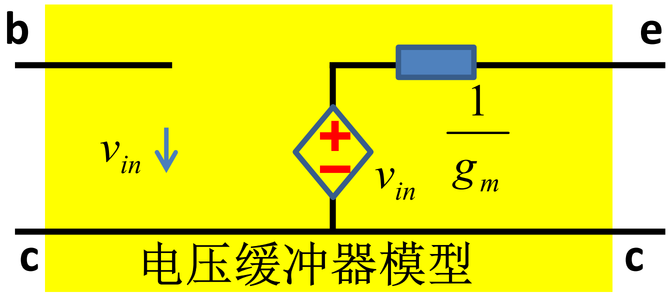
$$\mathbf{g}=\begin{bmatrix}\dfrac{1}{r_{be}+r_{ce}+g_m r_{be} r_{ce}} & -\dfrac{r_{ce}}{r_{be}+r_{ce}+g_m r_{be} r_{ce}}\\ \dfrac{r_{ce}+g_m r_{be} r_{ce}}{r_{be}+r_{ce}+g_m r_{be} r_{ce}} & \dfrac{1}{g_{be}+g_{ce}+g_m}\end{bmatrix}$$

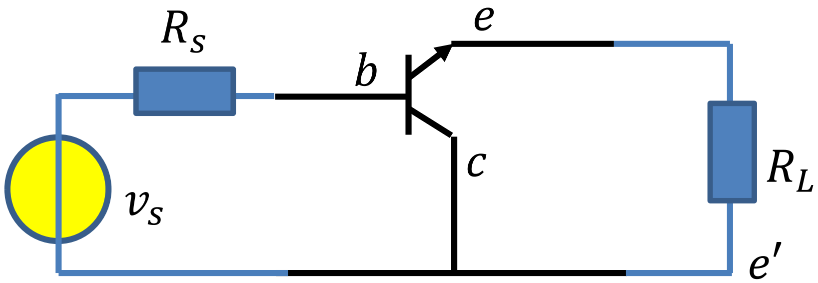
$$=\begin{bmatrix}0.0249\mu S & -0.00249\\ 0.9998 & 24.9314\Omega\end{bmatrix}$$

$$\approx\begin{bmatrix}0 & 0\\ 1 & \dfrac{1}{g_m}\end{bmatrix}=\begin{bmatrix}0 & 0\\ 1 & 25\Omega\end{bmatrix}$$

自行推导g参量矩阵
自行证明单向化条件

$R_S << r_{be} = 10k\Omega$





$$A_{v,CC}=\frac{R_L}{\frac{1}{g_m}+R_L}=\frac{g_m R_L}{1+g_m R_L}$$

晶体管三种组态放大器抽象小结

- CE组态是跨导放大器
  - $R_S \ll r_{be}, R_L \ll r_{ce}$
- CB组态是电流缓冲器
  - $R_L \ll r_{ce}$
- CC组态是电压缓冲器
  - $R_S \ll r_{be}$

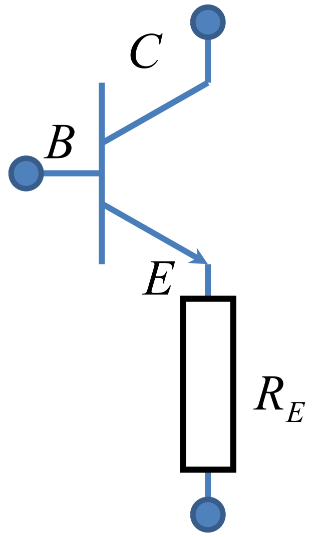
- CE组态是反相放大器
- CB组态是同相放大器
- CC组态是同相放大器

$$A_{v,CE} = -g_m R_L$$

$$A_{v,CB} = \frac{g_m}{1 + g_m R_S} R_L$$

$$A_{v,CC} = \frac{g_m R_L}{1 + g_m R_L}$$

作业5：串联负反馈

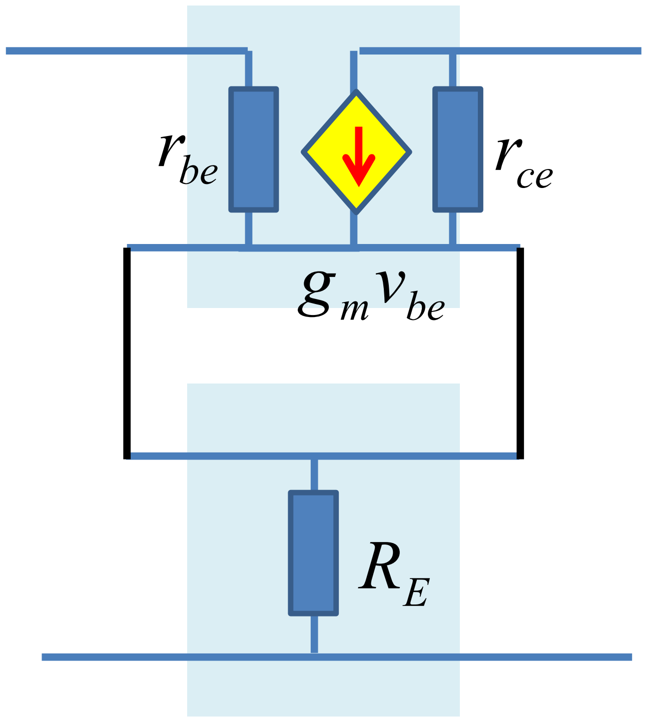


$g_m = 40mS$

$r_{be} = 10k\Omega$

$r_{ce} = 100k\Omega$

$R_E = 100\Omega, 1k\Omega$



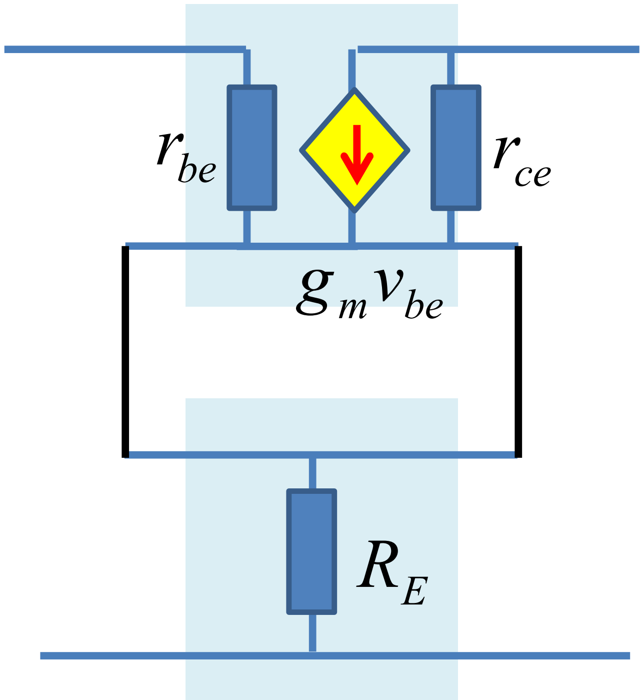
- 负反馈电阻**R_E**和**BJT**是串串连接关系，求
  - 总导纳参量**y**
    - 先求总阻抗参量**z**
    - 先符号运算，再代入具体数值
  - 思考：如果负反馈电阻很大，串串负反馈跨导放大器的输入电阻、输出电阻、跨导增益有什么规律可循？

$$g_m r_{be} >> 1; g_m r_{ce} >> 1;$$

$$r_{be}, r_{ce} >> R_E; g_m R_E \overset{??}{>>} 1$$

串串连接z相加

$$\mathbf{y}_{BJT}=\begin{bmatrix} g_{be} & 0 \\ g_m & g_{ce} \end{bmatrix}=\begin{bmatrix} 0.1mS & 0 \\ 40mS & 0.01mS \end{bmatrix}$$



$$\mathbf{z}_{BJT}=\begin{bmatrix} r_{be} & 0 \\ -g_m r_{be} r_{ce} & r_{ce} \end{bmatrix}=\begin{bmatrix} 10k\Omega & 0 \\ -40M\Omega & 100k\Omega \end{bmatrix}$$

$$\mathbf{z}_F=\begin{bmatrix} R_E & R_E \\ R_E & R_E \end{bmatrix}=\begin{bmatrix} 1k\Omega & 1k\Omega \\ 1k\Omega & 1k\Omega \end{bmatrix}$$

$R_E=1k\Omega$

$$\mathbf{z}_{AF}=\mathbf{z}_{BJT}+\mathbf{z}_F$$

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

$$=\begin{bmatrix} 11k\Omega & 1k\Omega \\ -39.999M\Omega & 101k\Omega \end{bmatrix}$$

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

负反馈放大器

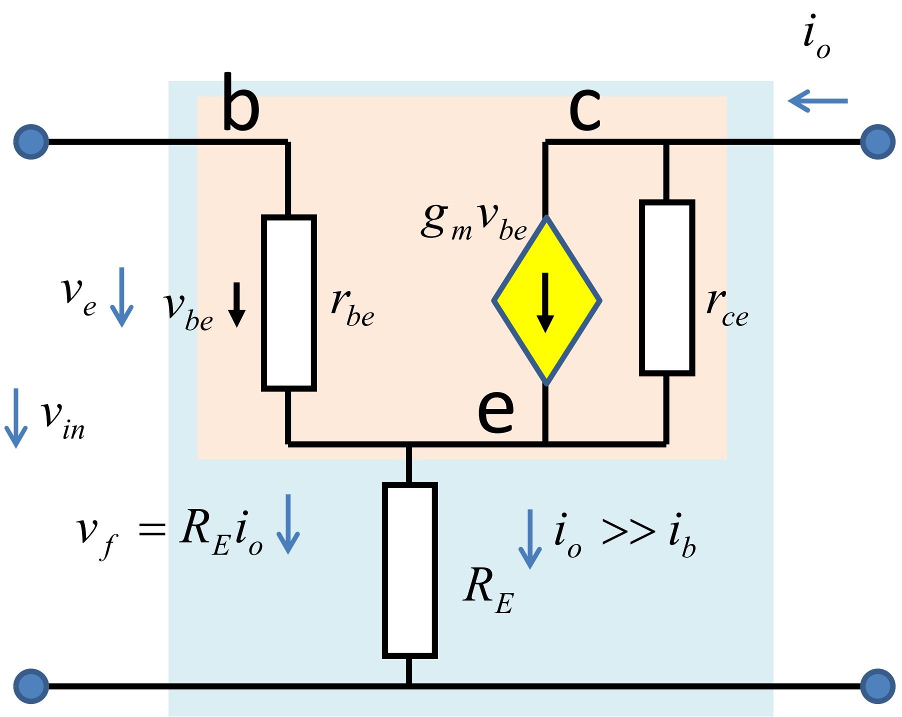
$r_{be}=10k\Omega$ $g_m=40mS$

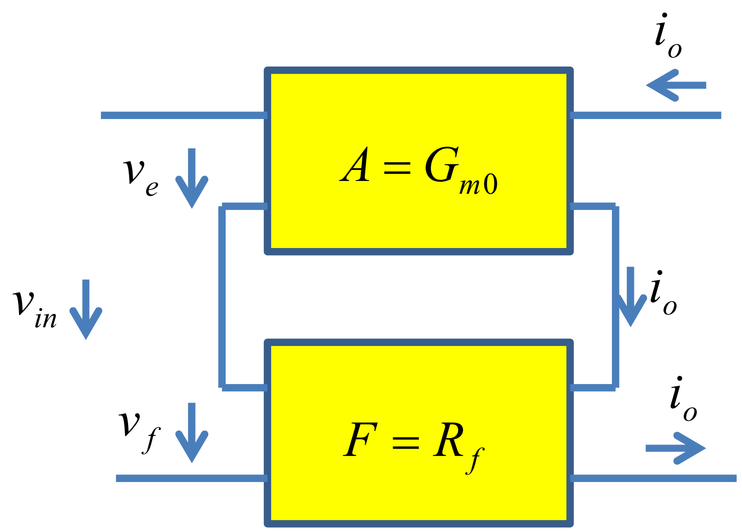
$r_{ce}=100k\Omega$ $R_E=100\Omega,1k\Omega$

单向化条件是少见负载情况
当成跨阻器不合适

$$R_S >> g_m R_E r_{be}=400k\Omega \text{或} R_L >> g_m R_E r_{ce}=4M\Omega$$

串串连接负反馈
检测输出电流，形成反馈电压
负反馈稳定输出电流，形成接近理想的压控流源





压控流源最适参量为y参量

y_{21}就是压控流源控制系数

导纳参量

$$\mathbf{z}_{AF}=\begin{bmatrix} r_{be}+R_E & R_E \\ -g_m r_{be} r_{ce}+R_E & r_{ce}+R_E \end{bmatrix}=\begin{bmatrix} 11k\Omega & 1k\Omega \\ -39.999M\Omega & 101k\Omega \end{bmatrix}$$

R_E=1kΩ

$$\mathbf{y}_{AF}=\mathbf{z}_{AF}^{-1}=\begin{bmatrix} 0.0024568 & -0.0000243 \\ 0.9729749 & 0.0002676 \end{bmatrix} mS \approx \begin{bmatrix} 0.0025 & 0.0000 \\ 0.9730 & 0.0003 \end{bmatrix} mS$$

$$|y_{12}y_{21}| << |(y_{11}+G_S)(y_{22}+G_L)| \qquad R_S << r_{be} \text{或} R_L << r_{ce}$$

单向化条件是最常见负载情况
视为跨导器是极为适当的

R_E=100Ω

$$\mathbf{z}_F=\begin{bmatrix} R_E & R_E \\ R_E & R_E \end{bmatrix}=\begin{bmatrix} 100\Omega & 100\Omega \\ 100\Omega & 100\Omega \end{bmatrix}$$

$$\mathbf{z}_{AF}=\mathbf{z}_{BJT}+\mathbf{z}_F=\begin{bmatrix} r_{be}+R_E & R_E \\ -g_m r_{be} r_{ce}+R_E & r_{ce}+R_E \end{bmatrix}=\begin{bmatrix} 10.1k\Omega & 0.1k\Omega \\ -39.9999M\Omega & 100.1k\Omega \end{bmatrix}$$

$$\mathbf{y}_{AF}=\mathbf{z}_{AF}^{-1}=\begin{bmatrix} 0.0199761 & -0.0000200 \\ 7.9824 & 0.0020156 \end{bmatrix} mS \approx \begin{bmatrix} 0.0200 & 0.0000 \\ 7.9824 & 0.0020 \end{bmatrix} mS$$

纯数值求解到此结束

但单看这些数值，不能提供任何帮助我们进行电路设计的提示，
若要形成概念性理解并用于电路设计，需要通用的符号表述

尝试给出通用公式

$$\mathbf{z}_{AF}=\mathbf{z}_{BJT}+\mathbf{z}_{F}=\begin{bmatrix} r_{be}+R_E & R_E \\ -g_m r_{be} r_{ce}+R_E & r_{ce}+R_E \end{bmatrix}$$

$$\mathbf{y}_{AF}=\mathbf{z}_{AF}^{-1}=\begin{bmatrix} r_{be}+R_E & R_E \\ -g_m r_{be} r_{ce}+R_E & r_{ce}+R_E \end{bmatrix}^{-1}$$

$$=\frac{1}{r_{be}r_{ce}(1+g_m R_E)+(r_{be}+r_{ce})R_E}\begin{bmatrix} r_{ce}+R_E & -R_E \\ g_m r_{be} r_{ce}-R_E & r_{be}+R_E \end{bmatrix}$$

$$=\begin{bmatrix} \dfrac{r_{ce}+R_E}{r_{be}r_{ce}(1+g_m R_E)+(r_{be}+r_{ce})R_E} & -\dfrac{R_E}{r_{be}r_{ce}(1+g_m R_E)+(r_{be}+r_{ce})R_E} \\ \dfrac{g_m r_{be} r_{ce}-R_E}{r_{be}r_{ce}(1+g_m R_E)+(r_{be}+r_{ce})R_E} & \dfrac{r_{be}+R_E}{r_{be}r_{ce}(1+g_m R_E)+(r_{be}+r_{ce})R_E} \end{bmatrix}$$

符号运算结果也太复杂了，无法形成有效记忆，需要进一步化简
下一步化简需要知道数值之间的相对大小，留大弃小

$r_{be}=10k\Omega$ $g_m=40mS$ $1+g_m R_E=5,41$

$r_{ce}=100k\Omega$ $R_E=100\Omega,1k\Omega$

$r_{be}r_{ce}=1000M\Omega^2$

$(r_{be}+r_{ce})R_E=11M\Omega^2,110M\Omega^2$

化简原则

留大弃小

$$\mathbf{y}_{AF}=\mathbf{z}_{AF}^{-1}=\begin{bmatrix} r_{be}+R_E & R_E \\ -g_m r_{be} r_{ce}+R_E & r_{ce}+R_E \end{bmatrix}^{-1}$$

$g_m r_{be}>>1; g_m r_{ce}>>1;$

$r_{be}, r_{ce}>>R_E$

$$=\begin{bmatrix} \frac{r_{ce}+R_E}{r_{be}r_{ce}(1+g_mR_E)+(r_{be}+r_{ce})R_E} & -\frac{R_E}{r_{be}r_{ce}(1+g_mR_E)+(r_{be}+r_{ce})R_E} \\ \frac{g_m r_{be} r_{ce}-R_E}{r_{be}r_{ce}(1+g_mR_E)+(r_{be}+r_{ce})R_E} & \frac{r_{be}+R_E}{r_{be}r_{ce}(1+g_mR_E)+(r_{be}+r_{ce})R_E} \end{bmatrix}$$

$$\approx\begin{bmatrix} \frac{r_{ce}}{r_{be}r_{ce}(1+g_mR_E)} & -\frac{R_E}{r_{be}r_{ce}(1+g_mR_E)} \\ \frac{g_m r_{be} r_{ce}}{r_{be}r_{ce}(1+g_mR_E)} & \frac{r_{be}}{r_{be}r_{ce}(1+g_mR_E)} \end{bmatrix}$$

$$=\begin{bmatrix} \frac{1}{r_{be}(1+g_mR_E)} & -\frac{R_E}{r_{be}r_{ce}(1+g_mR_E)} \\ \frac{g_m}{1+g_mR_E} & \frac{1}{r_{ce}(1+g_mR_E)} \end{bmatrix}\approx\begin{bmatrix} \frac{1}{r_{be}(1+g_mR_E)} & 0 \\ \frac{g_m}{1+g_mR_E} & \frac{1}{r_{ce}(1+g_mR_E)} \end{bmatrix}=\frac{\mathbf{y}_{BJT}}{1+g_mR_E}$$

这个结论很容易记忆，方便用于电路设计，有较大的g_mR_E，即可通过负反馈获得接近理想压控流源的跨导放大器

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

$R_S<<r_{be}$或$R_L<<r_{ce}$

单向化条件是最常见负载情况
基本跨导放大器模型是极为适当的

是否提前化简？更简单

$$\mathbf{y}_{AF}=\mathbf{z}_{AF}^{-1}=\begin{bmatrix} r_{be}+R_E & R_E \\ -g_m r_{be} r_{ce}+R_E & r_{ce}+R_E \end{bmatrix}^{-1} \approx \begin{bmatrix} r_{be} & R_E \\ -g_m r_{be} r_{ce} & r_{ce} \end{bmatrix}^{-1}$$

$$=\begin{bmatrix} \dfrac{1}{r_{be}(1+g_m R_E)} & -\dfrac{R_E}{r_{be} r_{ce}(1+g_m R_E)} \\ \dfrac{g_m}{1+g_m R_E} & \dfrac{1}{r_{ce}(1+g_m R_E)} \end{bmatrix}$$

$$\approx \begin{bmatrix} \dfrac{1}{r_{be}(1+g_m R_E)} & 0 \\ \dfrac{g_m}{1+g_m R_E} & \dfrac{1}{r_{ce}(1+g_m R_E)} \end{bmatrix}=\frac{\mathbf{y}_{BJT}}{1+g_m R_E}$$

问题简化多了……

10+1~10

里面是否包含了可普遍推广的东西？

2端口到1端口的作用系数：反馈系数

理想反馈网络

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

$$\approx\begin{bmatrix} r_{be} & R_E \\ -g_m r_{be} r_{ce} & r_{ce} \end{bmatrix}=\begin{bmatrix} r_{be} & 0 \\ -g_m r_{be} r_{ce} & r_{ce} \end{bmatrix}+\begin{bmatrix} 0 & R_E \\ 0 & 0 \end{bmatrix}=\mathbf{z}_{BJT}+\mathbf{z}_{F,ideal}$$

$$\mathbf{y}_{AF}=\mathbf{z}_{AF}^{-1}\approx\left(\mathbf{z}_{BJT}+\mathbf{z}_{F,ideal}\right)^{-1}\approx\frac{\mathbf{y}_{BJT}}{1+g_m R_E}$$

接近理想压控流源

形式上是否可推广？？

$$\mathbf{y}_{F,ideal}=\begin{bmatrix} 0 & G_f \\ 0 & 0 \end{bmatrix}$$

$$\mathbf{z}_{AF}=\mathbf{y}_{AF}^{-1}=\left(\mathbf{y}_A+\mathbf{y}_{F,ideal}\right)^{-1}\approx\frac{\mathbf{z}_A}{1+R_m G_f}$$

接近理想流控压源

$$\mathbf{z}_A=\begin{bmatrix} r_{in} & 0 \\ R_{m0} & r_{out} \end{bmatrix}$$

$$\mathbf{y}_A=\begin{bmatrix} g_{in} & 0 \\ -R_{m0} g_{in} g_{out} & g_{out} \end{bmatrix}$$

h参量，g参量？？

一般性的形式化的负反馈放大器分析套路1

串串连接z相加，并并连接y相加，串并连接h相加，并串连接g相加

放大网络一般是单向网络或准单向网络，**12**元素可视为**0**

负反馈网络多为线性互易无源元件构成的互易网络，$\mathbf{p}_{F,12}=\pm\mathbf{p}_{F,21}$

$$\mathbf{p}_{AF}=\mathbf{p}_{A}+\mathbf{p}_{F}=\begin{bmatrix} p_{A,11} & 0 \\ p_{A,21} & p_{A,22} \end{bmatrix}+\begin{bmatrix} p_{F,11} & p_{F,12} \\ p_{F,21} & p_{F,22} \end{bmatrix}$$

$$=\begin{bmatrix} p_{A,11}+p_{F,11} & p_{F,12} \\ p_{A,21}+p_{F,21} & p_{A,22}+p_{F,22} \end{bmatrix}$$

负反馈构成闭环系统，称为闭环放大器

$$\approx\begin{bmatrix} p_{A,11}+p_{F,11} & 0 \\ p_{A,21} & p_{A,22}+p_{F,22} \end{bmatrix}+\begin{bmatrix} 0 & p_{F,12} \\ 0 & 0 \end{bmatrix}=\mathbf{p}_{A,openloop}+\mathbf{p}_{F,ideal}$$

无源负反馈网络提供的端口**1**到端口**2**作用关系远远小于有源放大网络提供的端口**1**到端口**2**作用关系，故而可以忽略不计

负反馈网络提供的端口**1**和端口**2**的端口阻抗或导纳，有可能比放大网络自身的端口阻抗或导纳影响力更大，被称为负反馈网络的负载效应，在原始放大器基础上，在两个端口加上负反馈网络等效负载：开环放大器

2端口到**1**端口的反向作用被单独提取出来作为理想反馈网络

扣除**2**端口到**1**端口反馈作用后的单向网络，被称为开环放大器

串串连接，端口**2**串联检测输出电流，端口**1**串联形成反馈电压，负反馈稳定输出电流，故而形成接近理想的压控流源，理想压控流源的最适参量为**y**参量，故而串串连接**z**相加，之后再求逆获得最适**y**参量

并并连接，**…**理想的流控压源，**…**，故而并并连接**y**相加，之后再求逆获得最适**z**参量

串并连接，**…**理想的压控压源，**…**，故而串并连接**h**相加，之后再求逆获得最适**g**参量

并串连接，**…**理想的流控流源，**…**，故而并串连接**g**相加，之后再求逆获得最适**h**参量

一般性的形式化的负反馈放大器分析套路2

串串连接，端口2串联检测输出电流，端口1串联形成反馈电压，负反馈稳定输出电流，故而形成接近理想的压控流源，理想压控流源的最适参量为y参量，故而串串连接z相加，之后再求逆获得最适y参量

并并连接，…理想的流控压源，…，故而并并连接y相加，之后再求逆获得最适z参量

串并连接，…理想的压控压源，…，故而串并连接h相加，之后再求逆获得最适g参量

并串连接，…理想的流控流源，…，故而并串连接g相加，之后再求逆获得最适h参量

$$\mathbf{p}_{AF}=\mathbf{p}_{A}+\mathbf{p}_{F}\approx\begin{bmatrix} p_{A,11}+p_{F,11} & 0 \\ p_{A,21} & p_{A,22}+p_{F,22}\end{bmatrix}+\begin{bmatrix}0 & p_{F,12}\\ 0 & 0\end{bmatrix}=\mathbf{p}_{A,openloop}+\mathbf{p}_{F,ideal}$$

$$=\begin{bmatrix} p_{in0} & 0 \\ -A_0 p_{in0} p_{out0} & p_{out0}\end{bmatrix}+\begin{bmatrix}0 & F\\ 0 & 0\end{bmatrix}=\begin{bmatrix} q_{in0} & 0 \\ A_0 & q_{out0}\end{bmatrix}^{-1}+\begin{bmatrix}0 & F\\ 0 & 0\end{bmatrix}$$

理想反馈系数

开环放大倍数

开环放大器输入/输出阻抗/导纳

闭环放大器参量矩阵12元素和21元素必然一正一负才是负反馈

$$\mathbf{q}_{AF}=\mathbf{p}_{AF}^{-1}\approx\begin{bmatrix} p_{in0} & F \\ -A_0 p_{in0} p_{out0} & p_{out0}\end{bmatrix}^{-1}=\frac{1}{(1+A_0F)p_{in0}p_{out0}}\begin{bmatrix} p_{out0} & -F \\ A_0 p_{in0} p_{out0} & p_{in0}\end{bmatrix}$$

闭环最适参量矩阵近似是开环参量除以（$1+A_0F$）

$$=\frac{1}{1+A_0F}\begin{bmatrix} \frac{1}{p_{in0}} & \frac{-F}{p_{in0}p_{out0}} \\ A_0 & \frac{1}{p_{out0}}\end{bmatrix}=\begin{bmatrix} \frac{q_{in0}}{1+A_0F} & \frac{-Fq_{in0}q_{out0}}{1+A_0F} \\ \frac{A_0}{1+A_0F} & \frac{q_{out0}}{1+A_0F}\end{bmatrix}\approx\begin{bmatrix} \frac{q_{in0}}{1+A_0F} & 0 \\ \frac{A_0}{1+A_0F} & \frac{q_{out0}}{1+A_0F}\end{bmatrix}=\frac{1}{1+A_0F}\mathbf{q}_{A,openloop}$$

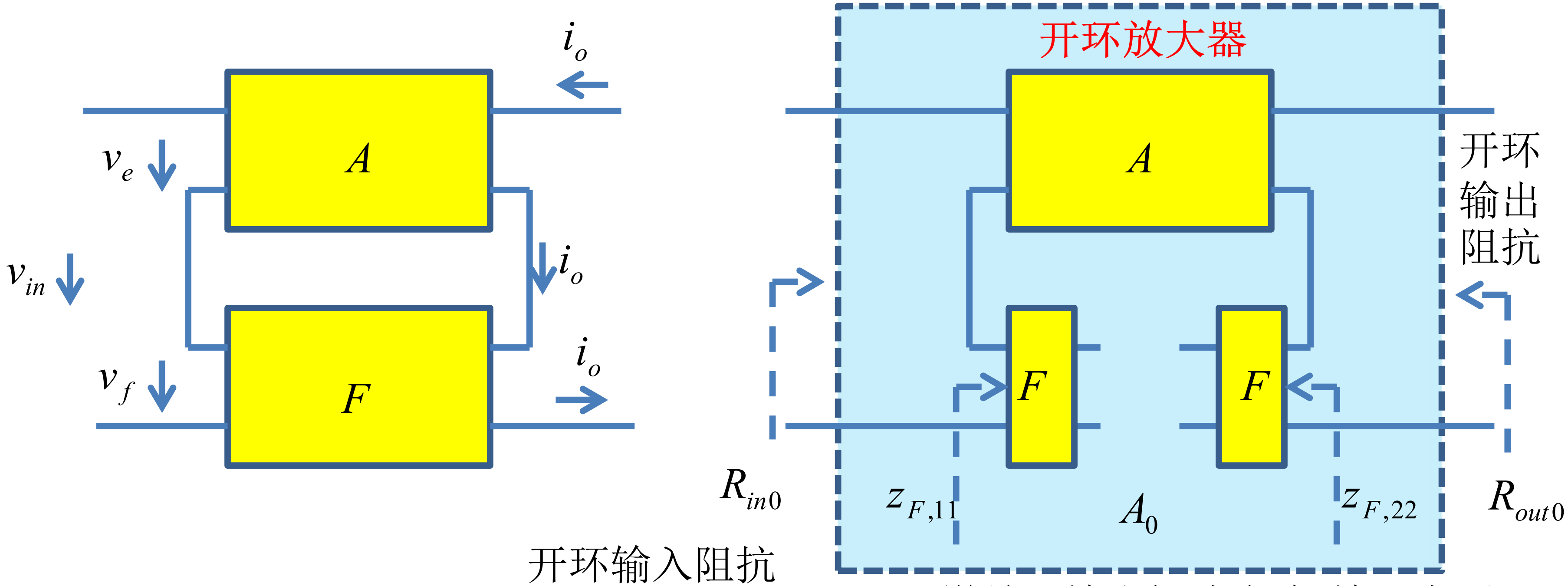
结论：闭环增益是开环增益除以（$1+A_0F$），闭环阻抗串联连接则开环阻抗乘以（$1+A_0F$），闭环阻抗并联连接则开环阻抗除以（$1+A_0F$）

开环放大器求例

负反馈放大器分析套路操作1

$$\mathbf{p}_{A,openloop} \approx \begin{bmatrix} p_{A,11}+p_{F,11} & 0 \\ p_{A,21} & p_{A,22}+p_{F,22} \end{bmatrix} = \begin{bmatrix} p_{A,11} & 0 \\ p_{A,21} & p_{A,22} \end{bmatrix} + \begin{bmatrix} p_{F,11} & 0 \\ 0 & p_{F,22} \end{bmatrix} = \mathbf{p}_A + \mathbf{p}_{F,Load}$$

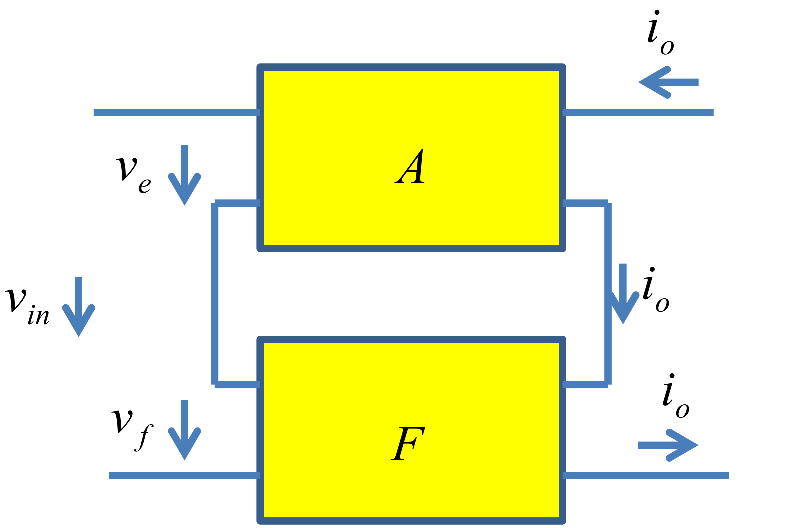
$$\mathbf{z}_{A,openloop} \approx \begin{bmatrix} z_{A,11}+z_{F,11} & 0 \\ z_{A,21} & z_{A,22}+z_{F,22} \end{bmatrix} = \begin{bmatrix} z_{A,11} & 0 \\ z_{A,21} & z_{A,22} \end{bmatrix} + \begin{bmatrix} z_{F,11} & 0 \\ 0 & z_{F,22} \end{bmatrix} = \mathbf{z}_A + \mathbf{z}_{F,Load}$$



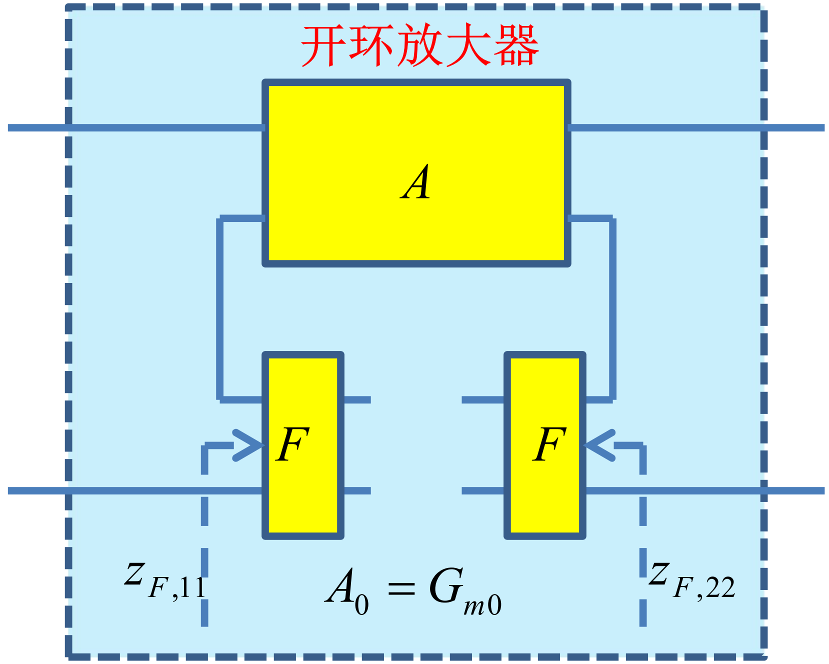
开环输入阻抗

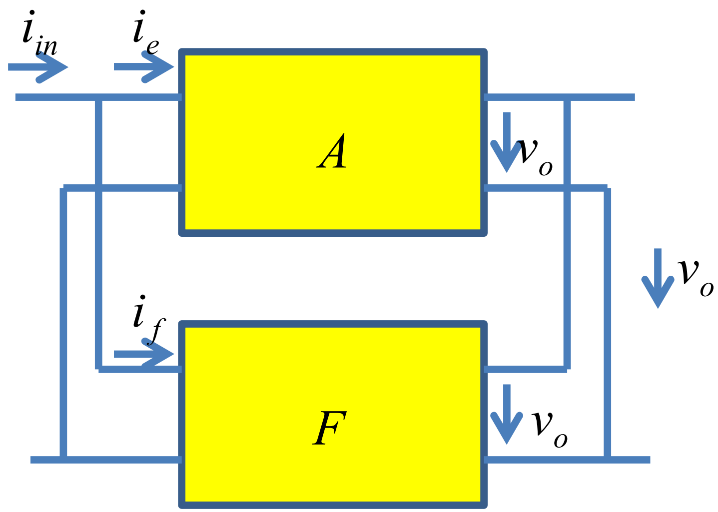
开环增益：输出短路电流/输入电压

开环放大器

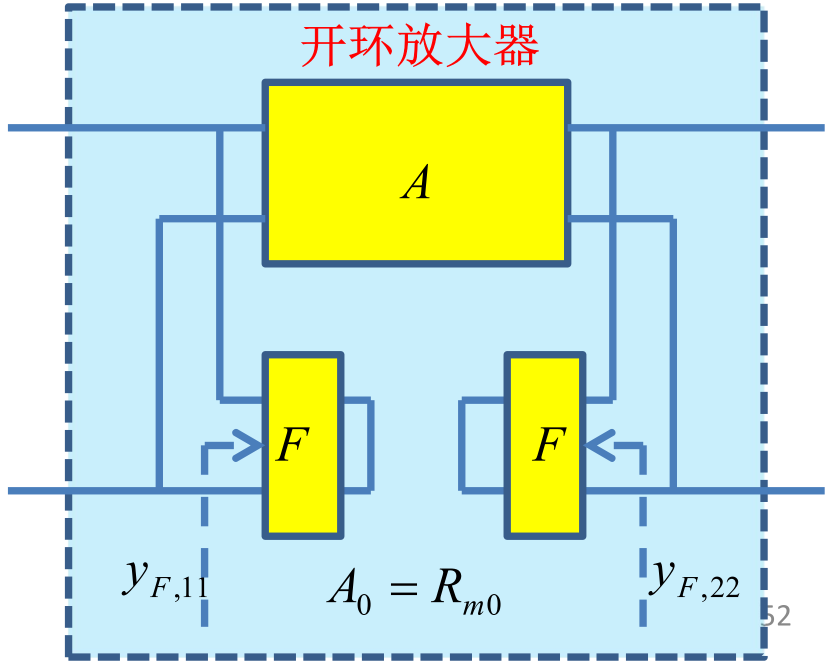


$$\mathbf{z}_{A,openloop} \approx \begin{bmatrix} z_{A,11} & 0 \\ z_{A,21} & z_{A,22} \end{bmatrix} + \begin{bmatrix} z_{F,11} & 0 \\ 0 & z_{F,22} \end{bmatrix}$$

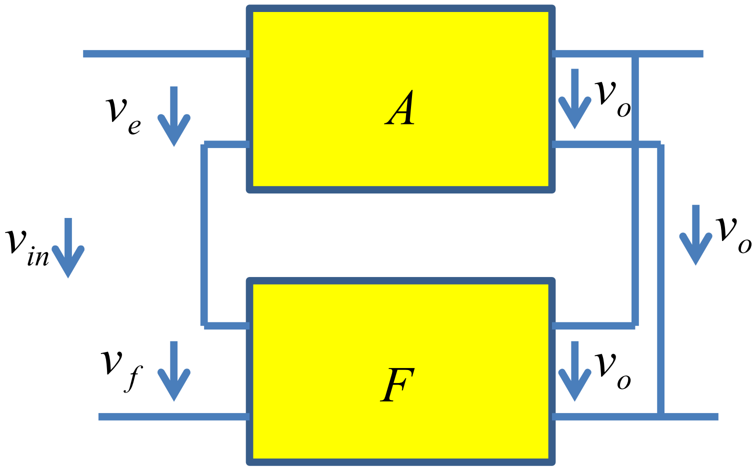




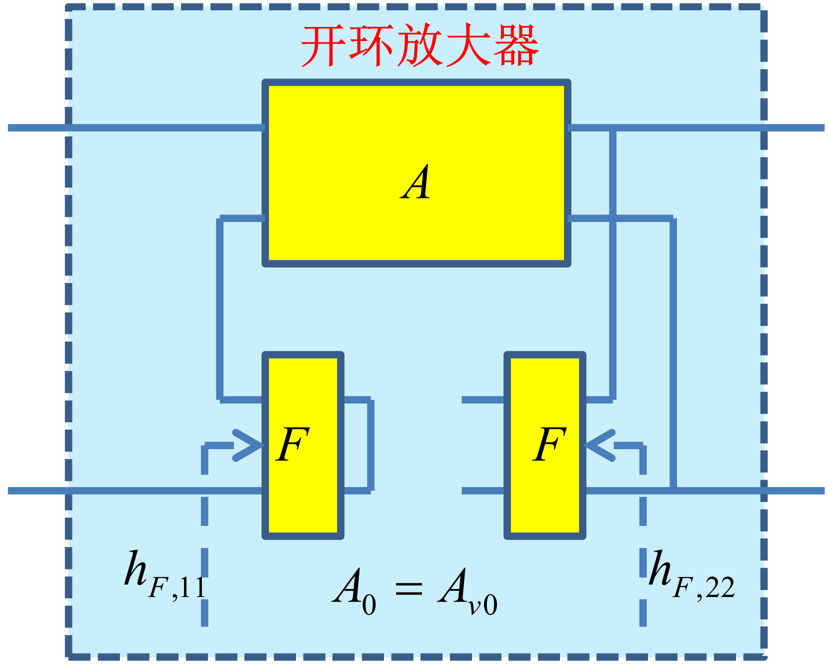
$$\mathbf{y}_{A,openloop} \approx \begin{bmatrix} y_{A,11} & 0 \\ y_{A,21} & y_{A,22} \end{bmatrix} + \begin{bmatrix} y_{F,11} & 0 \\ 0 & y_{F,22} \end{bmatrix}$$

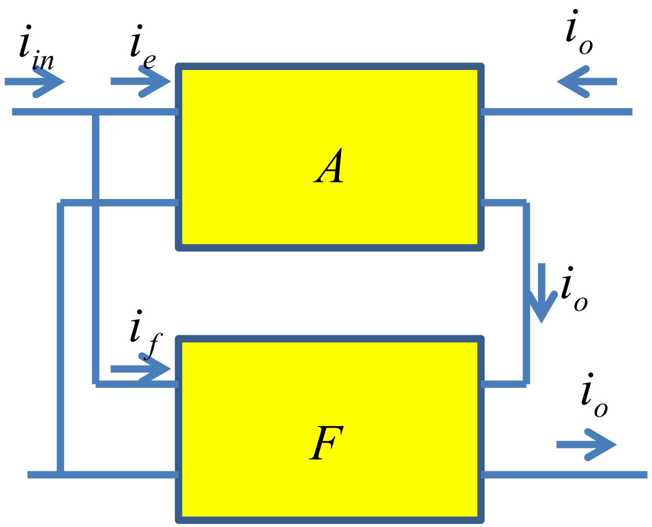


开环放大器

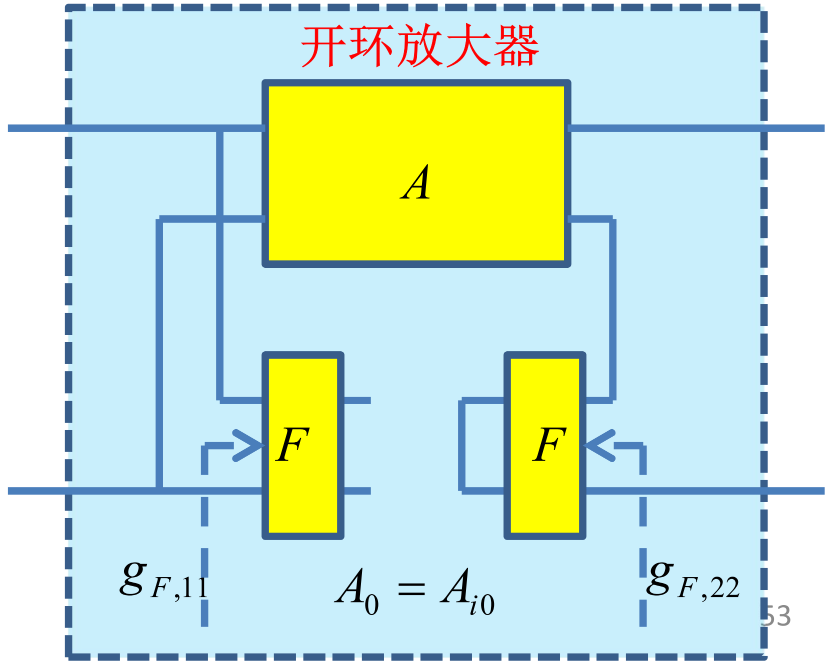


$$\mathbf{h}_{A,openloop} \approx \begin{bmatrix} h_{A,11} & 0 \\ h_{A,21} & h_{A,22} \end{bmatrix} + \begin{bmatrix} h_{F,11} & 0 \\ 0 & h_{F,22} \end{bmatrix}$$





$$\mathbf{g}_{A,openloop} \approx \begin{bmatrix} g_{A,11} & 0 \\ g_{A,21} & g_{A,22} \end{bmatrix} + \begin{bmatrix} g_{F,11} & 0 \\ 0 & g_{F,22} \end{bmatrix}$$

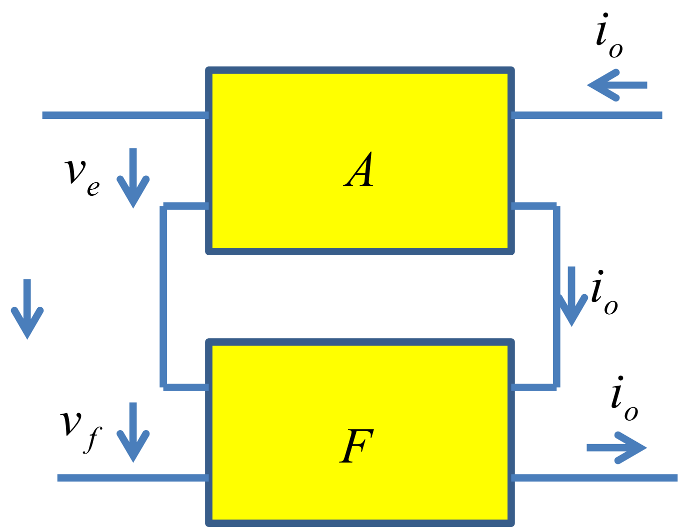


理想反馈系数求例

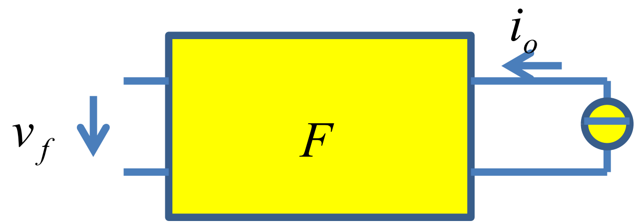
负反馈放大器分析操作套路2

$$\mathbf{p}_{AF}=\mathbf{p}_{A}+\mathbf{p}_{F}\approx\begin{bmatrix}p_{A,11}+p_{F,11} & 0\\ p_{A,21} & p_{A,22}+p_{F,22}\end{bmatrix}+\begin{bmatrix}0 & p_{F,12}\\ 0 & 0\end{bmatrix}$$

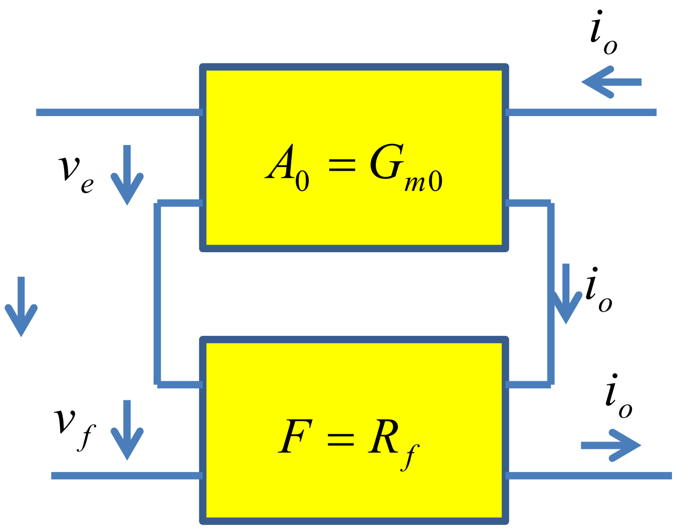
$$=\begin{bmatrix}p_{in0} & 0\\ -A_0 p_{in0}p_{out0} & p_{out0}\end{bmatrix}+\begin{bmatrix}0 & F\\ 0 & 0\end{bmatrix}=\mathbf{p}_{A,openloop}+\mathbf{p}_{F,ideal}$$



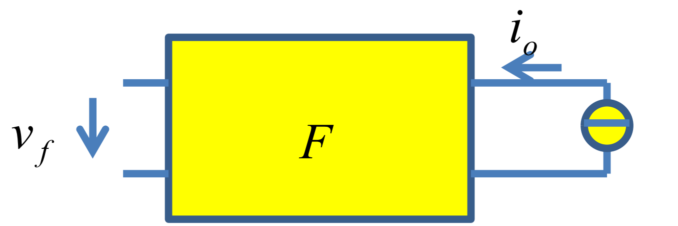
$$F=\frac{v_f}{i_o}=z_{F,12}$$



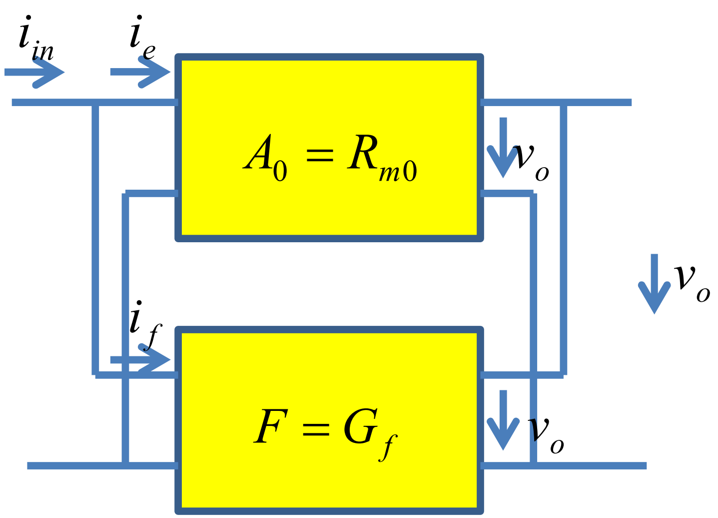
理想反馈系数



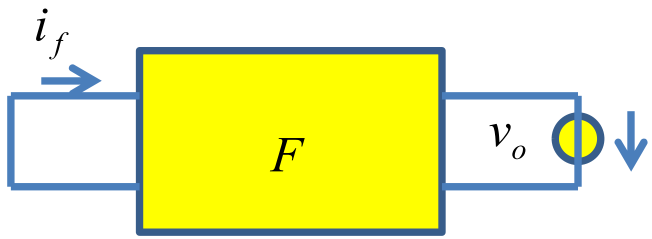
$$F = \frac{v_f}{i_o} = z_{F,12} = R_f$$



$$\begin{bmatrix} 0 & F \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & z_{F,12} \\ 0 & 0 \end{bmatrix}$$

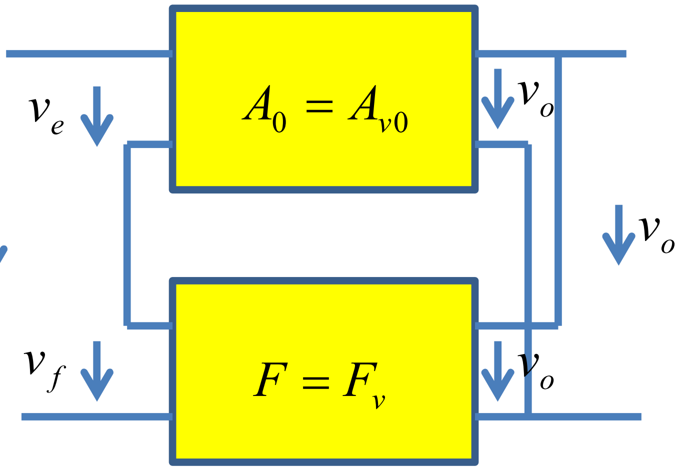


$$F = \frac{i_f}{v_o} = y_{F,12} = G_f$$

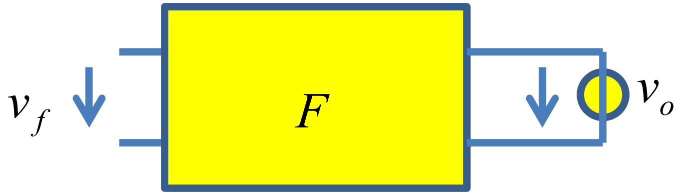


$$\begin{bmatrix} 0 & F \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & y_{F,12} \\ 0 & 0 \end{bmatrix}$$

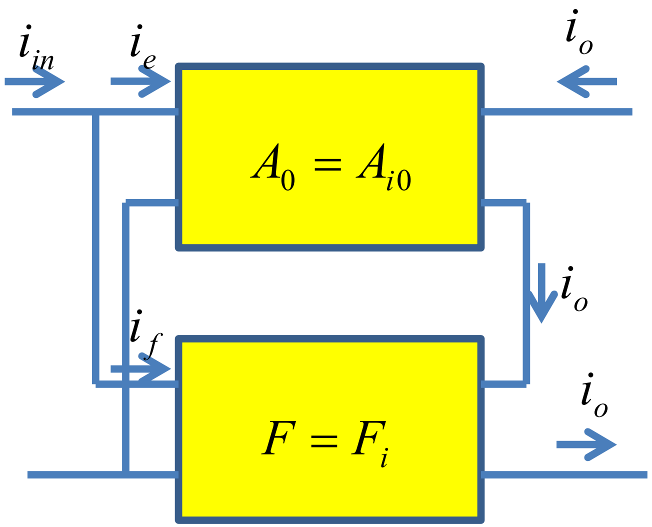
理想反馈系数



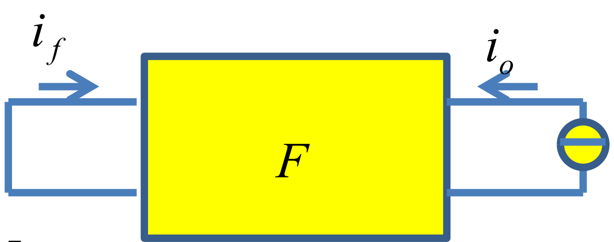
$$F = \frac{v_f}{v_o} = h_{F,12} = F_v$$



$$\begin{bmatrix} 0 & F \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & h_{F,12} \\ 0 & 0 \end{bmatrix}$$



$$F = \frac{i_f}{i_o} = g_{F,12} = F_i$$



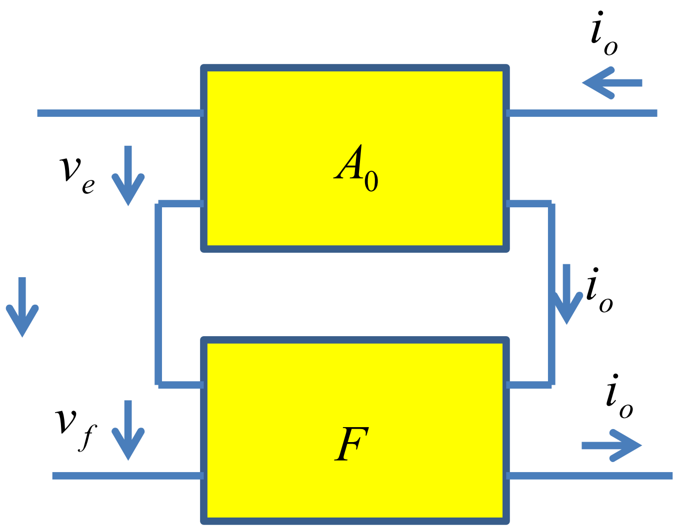
$$\begin{bmatrix} 0 & F \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & g_{F,12} \\ 0 & 0 \end{bmatrix}$$

闭环放大器参量

负反馈放大器分析操作套路3

$$\mathbf{q}_{AF}=\mathbf{p}_{AF}^{-1}\approx\begin{bmatrix}p_{in0} & F\\ -A_0p_{in0}p_{out0} & p_{out0}\end{bmatrix}^{-1}=\frac{1}{(1+A_0F)p_{in0}p_{out0}}\begin{bmatrix}p_{out0} & F\\ A_0p_{in0}p_{out0} & p_{in0}\end{bmatrix}$$

$$=\frac{1}{1+A_0F}\begin{bmatrix}\frac{1}{p_{in0}} & \frac{F}{p_{in0}p_{out0}}\\ A_0 & \frac{1}{p_{out0}}\end{bmatrix}=\begin{bmatrix}\frac{q_{in0}}{1+A_0F} & \frac{Fq_{in0}q_{out0}}{1+A_0F}\\ \frac{A_0}{1+A_0F} & \frac{q_{out0}}{1+A_0F}\end{bmatrix}\approx\begin{bmatrix}\frac{q_{in0}}{1+A_0F} & 0\\ \frac{A_0}{1+A_0F} & \frac{q_{out0}}{1+A_0F}\end{bmatrix}=\frac{1}{1+A_0F}\mathbf{q}_{A,openloop}$$

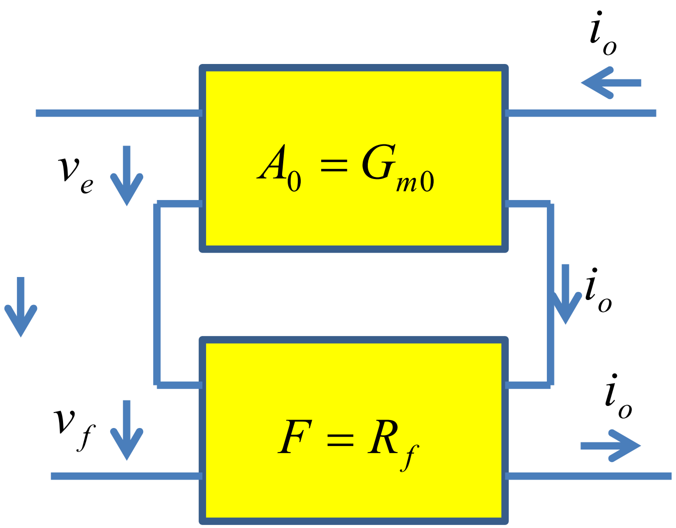


$$r_{inf}=(1+A_0F)r_{in0}=(1+G_{m0}R_f)r_{in0}$$

$$r_{outf}=(1+A_0F)r_{out0}=(1+G_{m0}R_f)r_{out0}$$

$$A_f=\frac{A_0}{1+A_0F}=\frac{G_{m0}}{1+G_{m0}R_f}=G_{mf}\overset{A_0F>>1}{\approx}\frac{1}{R_f}=\frac{1}{F}$$

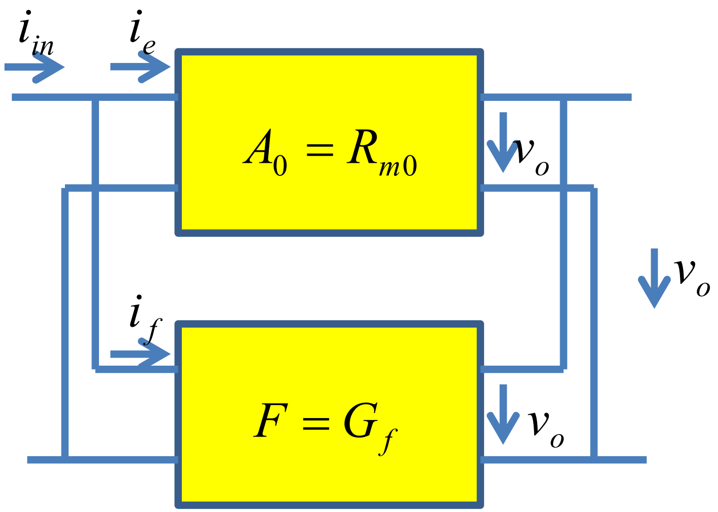
闭环放大器参量



$$r_{inf} = (1 + A_0 F) r_{in0} = (1 + G_{m0} R_f) r_{in0}$$

$$r_{outf} = (1 + A_0 F) r_{out0} = (1 + G_{m0} R_f) r_{out0}$$

$$A_f = \frac{A_0}{1 + A_0 F} = \frac{G_{m0}}{1 + G_{m0} R_f} = G_{mf} \overset{A_0 F >> 1}{\approx} \frac{1}{R_f} = \frac{1}{F}$$

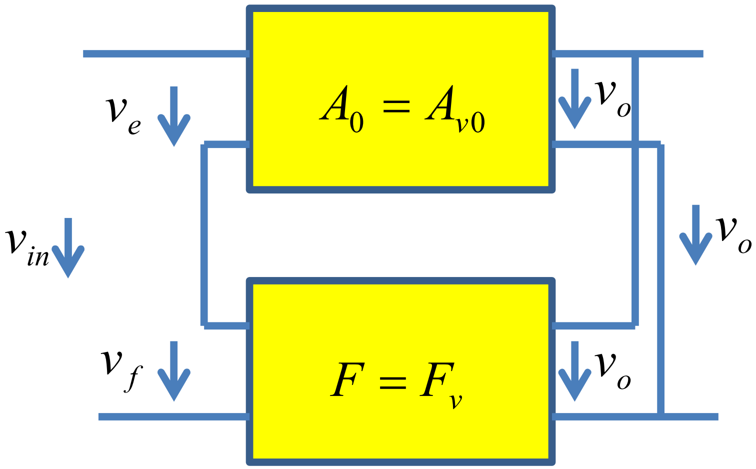


$$r_{inf} = \frac{r_{in0}}{1 + A_0 F} = \frac{r_{in0}}{1 + R_{m0} G_f}$$

$$r_{outf} = \frac{r_{out0}}{1 + A_0 F} = \frac{r_{out0}}{1 + R_{m0} G_f}$$

$$A_f = \frac{A_0}{1 + A_0 F} = \frac{R_{m0}}{1 + R_{m0} G_f} = R_{mf} \overset{A_0 F >> 1}{\approx} \frac{1}{G_f} = \frac{1}{F}$$

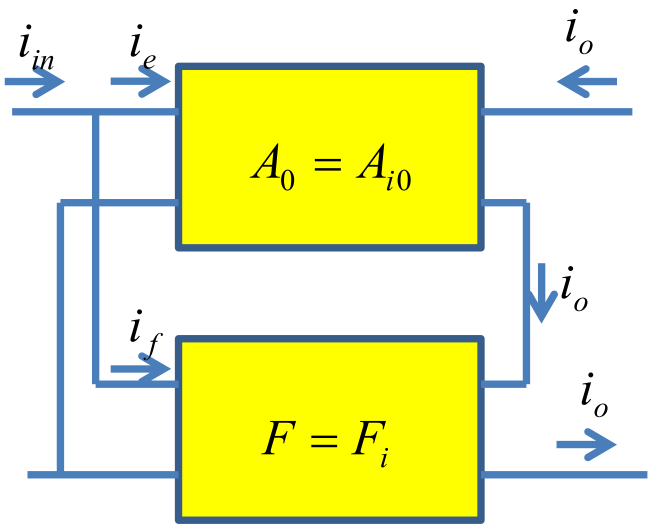
闭环放大器参量



$$r_{inf} = (1 + A_0 F) r_{in0} = (1 + A_{v0} F_v) r_{in0}$$

$$r_{outf} = \frac{r_{out0}}{1 + A_0 F} = \frac{r_{out0}}{1 + A_{v0} F_v}$$

$$A_f = \frac{A_0}{1 + A_0 F} = \frac{A_{v0}}{1 + A_{v0} F_v} = A_{vf} \overset{A_0 F >> 1}{\approx} \frac{1}{F_v} = \frac{1}{F}$$



$$r_{inf} = \frac{r_{in0}}{1 + A_0 F} = \frac{r_{in0}}{1 + A_{i0} F_i}$$

$$r_{outf} = (1 + A_0 F) r_{out0} = (1 + A_{i0} F_i) r_{out0}$$

$$A_f = \frac{A_0}{1 + A_0 F} = \frac{A_{i0}}{1 + A_{i0} F_i} = A_{if} \overset{A_0 F >> 1}{\approx} \frac{1}{F_i} = \frac{1}{F}$$

负反馈放大器分析总结

负反馈连接关系	检测、稳定	反馈、相减	形成	最适参量	运算获得	开环参量 R_{in} R_{out}	反馈系数	环路增益T	闭环最适参量（近似）
串串连接	输出电流 $v_f=R_f i_o$	反馈电压	压控流源	y参量	z相加，再求逆	G_{m0} $\mathbf{y}_o$	R_f	$G_{m0}R_f$	$\frac{\mathbf{y}_o}{1+T}$ $G_{mf}=\frac{G_{m0}}{1+T}$ $r_{inf}=r_{in0}(1+T)$ $r_{outf}=r_{out0}(1+T)$
并并连接	输出电压 $i_f=G_f v_o$	反馈电流	流控压源	z参量	y相加，再求逆	R_{m0} $\mathbf{z}_o$	G_f	$R_{m0}G_f$	$\frac{\mathbf{z}_o}{1+T}$ 输入阻抗、输出阻抗的影响变小了，故而接近理想受控源
串并连接	输出电压 $v_f=F_v v_o$	反馈电压	压控压源	g参量	h相加，再求逆	A_{v0} $\mathbf{g}_o$	F_v	$A_{v0}F_v$	$\frac{\mathbf{g}_o}{1+T}$
并串连接	输出电流 $i_f=F_i i_o$	反馈电流	流控流源	h参量	g相加，再求逆	A_{i0} $\mathbf{h}_o$	F_i	$A_{i0}F_i$	$\frac{\mathbf{h}_o}{1+T}$

闭环放大器类型由反馈连接关系决定：无论原始放大器是什么类型的放大器，开环放大器都应转换为对应最适参量表述：负反馈网络在输入、输出阻抗上的影响可能占优

拓展分析的目标

- 学会对计算结果给出一个合理的物理解释，充分简化、总结之后即可牢靠记忆，为电路设计打好铺垫
  - 电路设计是在原理性理解的基础上实施的
  - 请同学们深入研究并探讨每一个例题和作业题，为以后的电路设计打好坚实的基础
  - 在数学推导的前提下，给出一个物理或电路上的简单解释，便于记忆，方便电路设计