电子电路与系统基础I

习题课第十二讲

负反馈放大器分析

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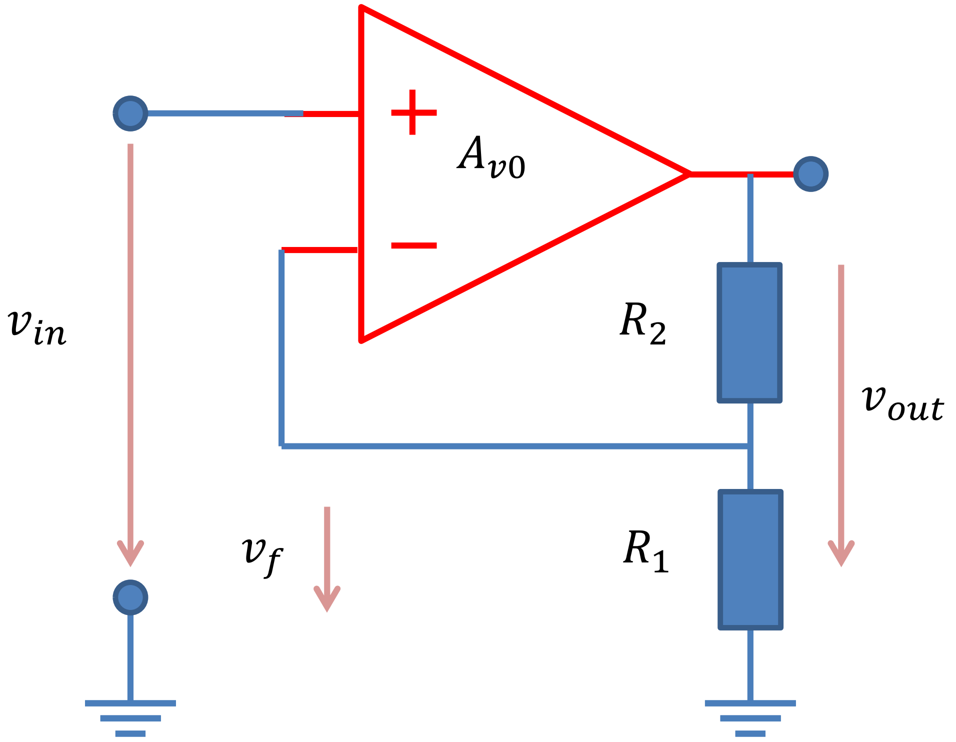
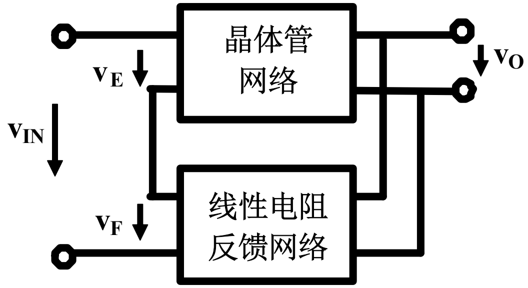
第10次作业

作业6 负反馈

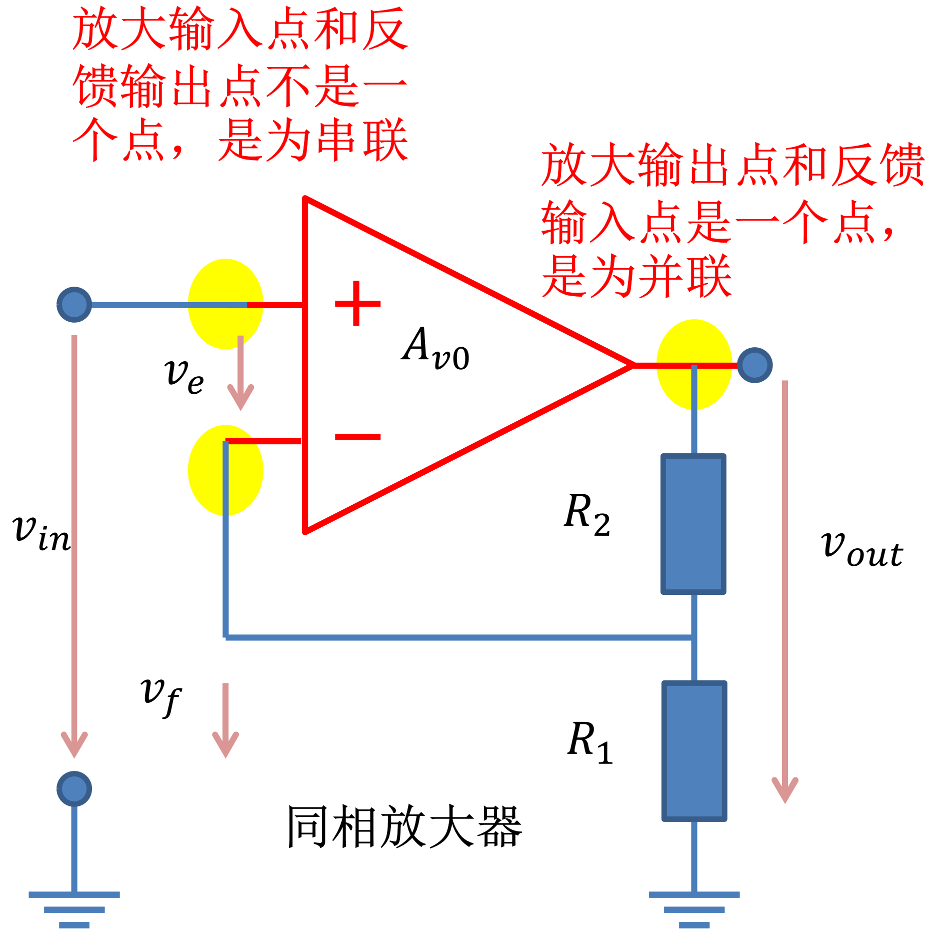


- 附加题：说明这是一个串并负反馈连接方式，故而形成的是接近理想的压控压源
  - 给出两个网络的二端口网络参量
  - 串并连接h相加
  - h求逆得g
    - 接近理想压控压源;$g_{11},g_{22},g_{12} \rightarrow 0$
    - g_{21}由反馈网络决定

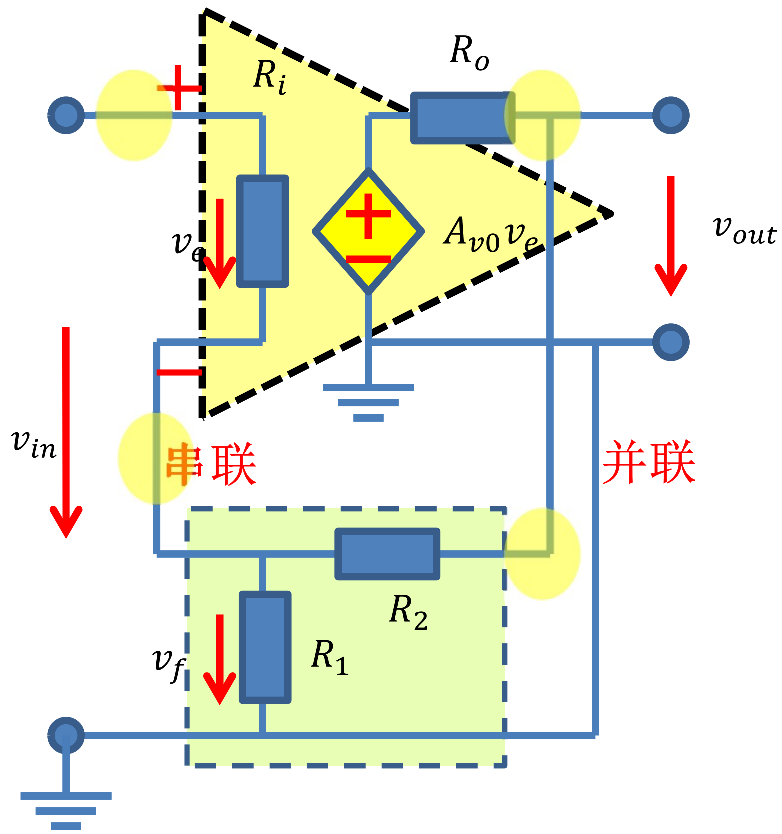


串并负反馈

串并连接关系



放大输入点和反
馈输出点不是一
个点，是为串联
放大输出点和反馈
输入点是一个点，
是为并联
+
−
A_{v0}
v_e
v_{in}
v_f
R_2
R_1
v_{out}
同相放大器

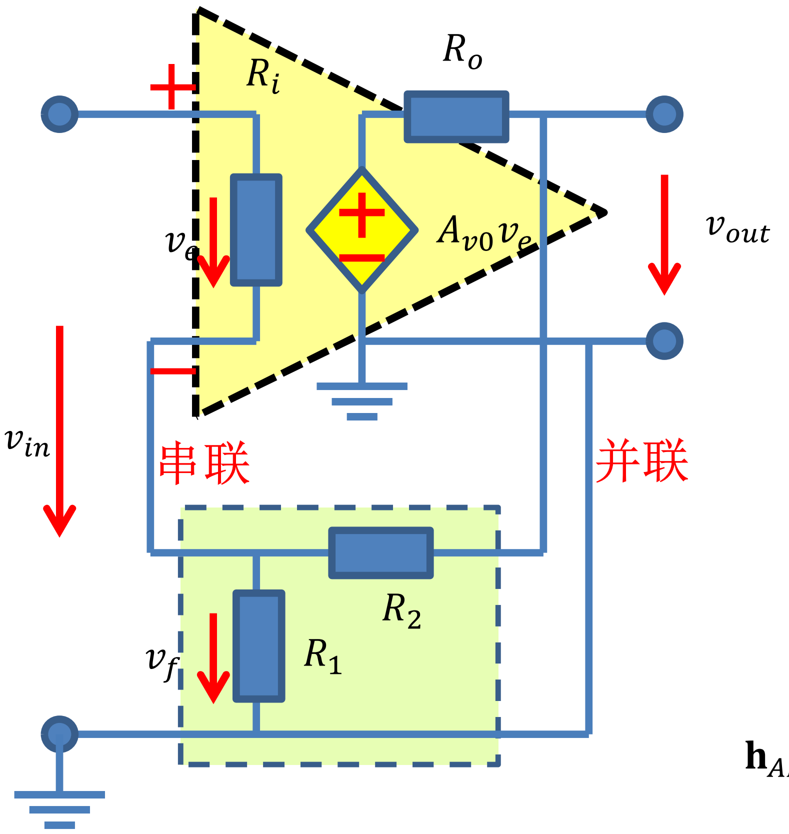


R_i
R_o
+
−
v_e
$A_{v0}v_e$
v_{out}
v_{in}
串联
并联
R_2
R_1
v_f

串并连接h参加

$$\mathbf{g}_A = \begin{bmatrix} G_i & 0 \\ A_{v0} & R_o \end{bmatrix}$$

电压放大器
最适参量g矩阵



$$\mathbf{h}_A = \mathbf{g}_A{}^{-1} = \begin{bmatrix} R_i & 0 \\ -A_{v0}R_iG_o & G_o \end{bmatrix}$$

串并连接h相加

$$\mathbf{h}_R = \begin{bmatrix} \dfrac{R_1R_2}{R_1+R_2} & \dfrac{R_1}{R_1+R_2} \\ -\dfrac{R_1}{R_1+R_2} & \dfrac{1}{R_1+R_2} \end{bmatrix}$$

$$\mathbf{h}_{AF} = \mathbf{h}_A + \mathbf{h}_R = \begin{bmatrix} R_i + \dfrac{R_1R_2}{R_1+R_2} & \dfrac{R_1}{R_1+R_2} \\ -A_{v0}R_iG_o - \dfrac{R_1}{R_1+R_2} & G_o + \dfrac{1}{R_1+R_2} \end{bmatrix}$$

开环放大与理想反馈的分解

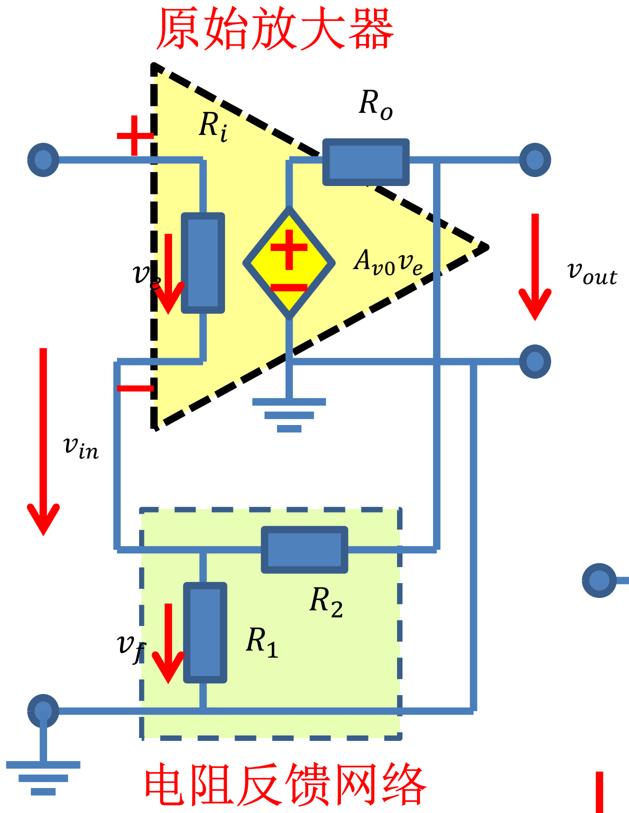
$$\mathbf{h}_{AF} = \mathbf{h}_A + \mathbf{h}_R = \begin{bmatrix} R_i + \dfrac{R_1R_2}{R_1+R_2} & \dfrac{R_1}{R_1+R_2} \\ -A_{v0}R_iG_o - \dfrac{R_1}{R_1+R_2} & G_o + \dfrac{1}{R_1+R_2} \end{bmatrix}$$

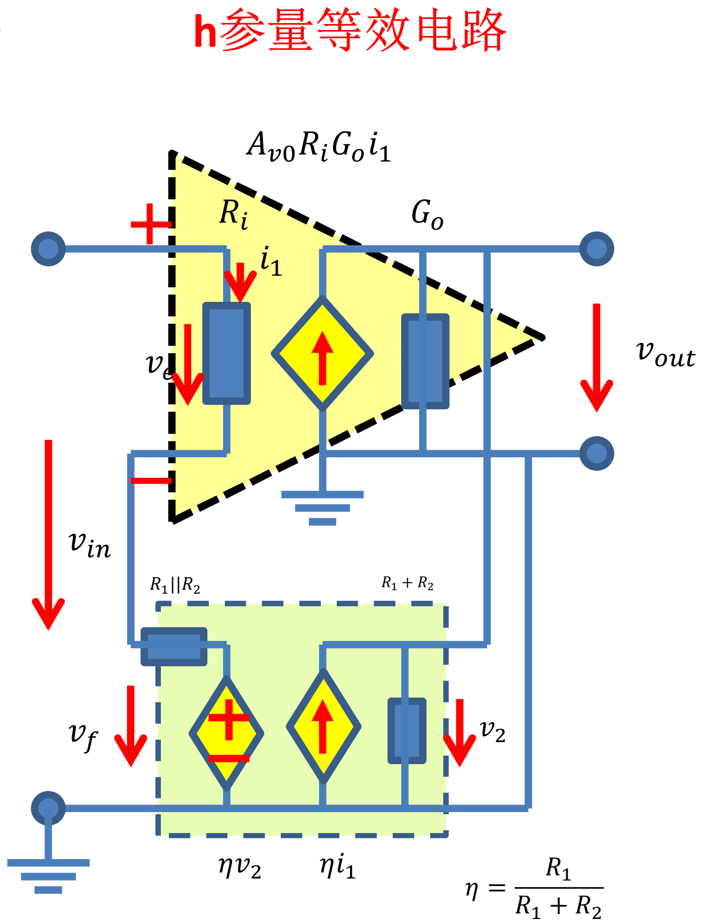
$$= \begin{bmatrix} R_i + \dfrac{R_1R_2}{R_1+R_2} & 0 \\ -A_{v0}R_iG_o - \dfrac{R_1}{R_1+R_2} & G_o + \dfrac{1}{R_1+R_2} \end{bmatrix} + \begin{bmatrix} 0 & \dfrac{R_1}{R_1+R_2} \\ 0 & 0 \end{bmatrix}$$

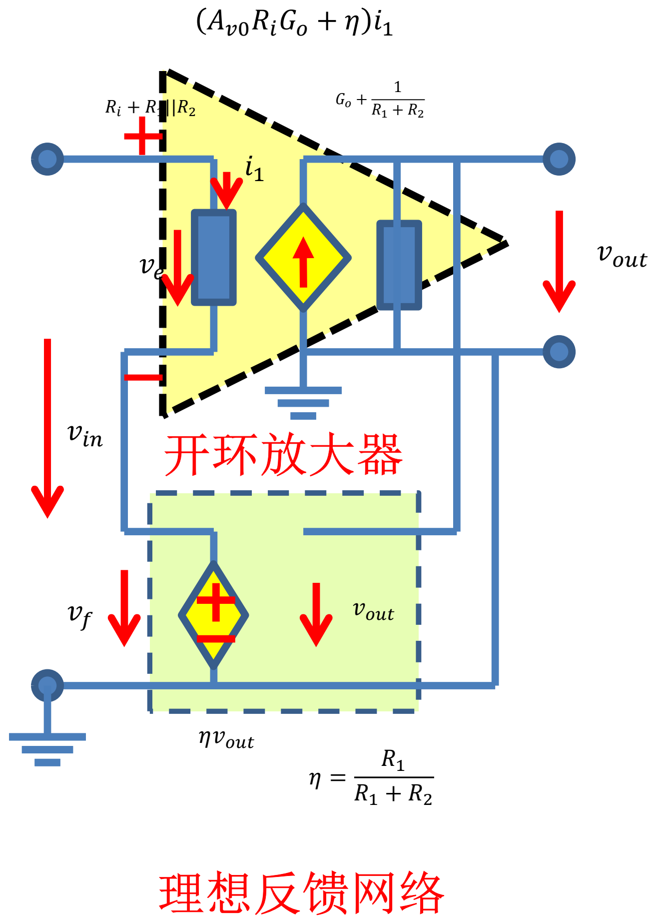
$$= \begin{bmatrix} r_{in} & 0 \\ -A_{vo}r_{in}g_{out} & g_{out} \end{bmatrix} + \begin{bmatrix} 0 & F_v \\ 0 & 0 \end{bmatrix} = \mathbf{h}_{Ao} + \mathbf{h}_F$$

开环放大器　　　理想反馈网络

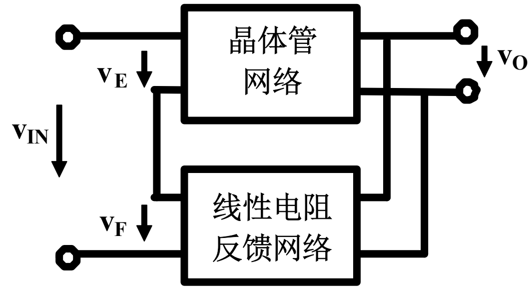
开环放大与理想反馈的分解电路模型







开环与闭环



串并负反馈

$$\mathbf{h}_{AF}=\mathbf{h}_A+\mathbf{h}_R=\begin{bmatrix} r_{in} & 0 \\ -A_{vo}r_{in}g_{out} & g_{out}\end{bmatrix}+\begin{bmatrix} 0 & F_v \\ 0 & 0\end{bmatrix}=\mathbf{h}_{Ao}+\mathbf{h}_F$$

串并连接：检测输出电压，形成反馈电压，从输入电压扣除反馈电压形成误差电压，作用到开环放大器后，稳定输出电压：形成压控压源：电压放大g最宜

$$\mathbf{g}_{Ao}=\mathbf{h}_{Ao}{}^{-1}=\begin{bmatrix} g_{in} & 0 \\ A_{vo} & r_{out}\end{bmatrix}$$

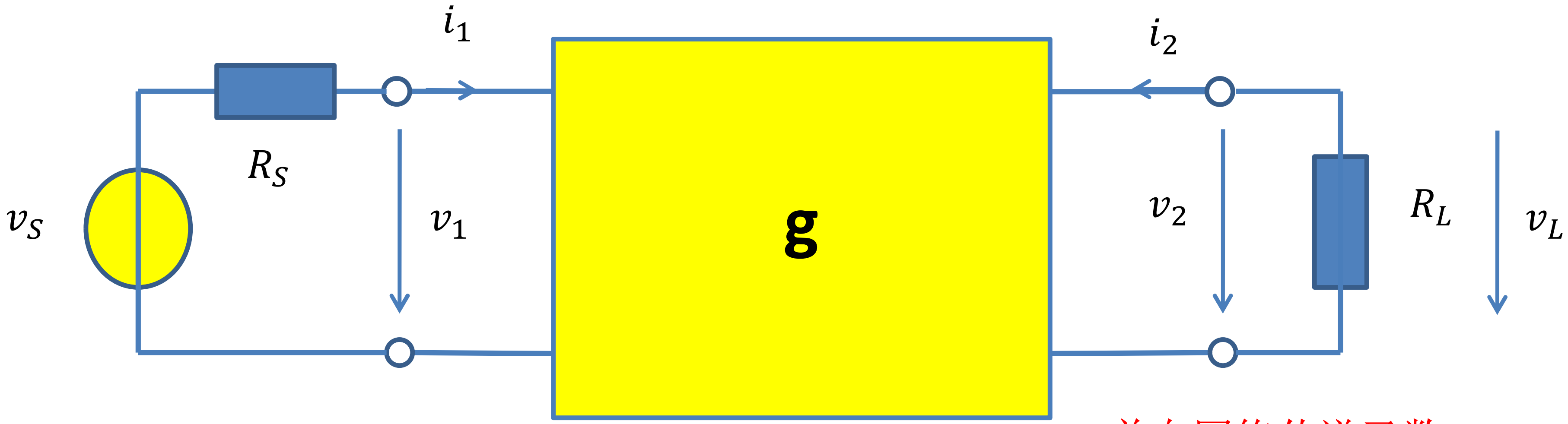
开环放大器：输入电阻$\mathbf{r_{in}}$，输出电阻$\mathbf{r_{out}}$，电压增益$\mathbf{A_{vo}}$

满足单向化条件

$$\mathbf{g}_{AF}=\mathbf{h}_{AF}{}^{-1}=\frac{1}{1+A_{vo}F_v}\begin{bmatrix} g_{in} & -F_v g_{in} r_{out} \\ A_{vo} & r_{out}\end{bmatrix}\approx\frac{1}{1+A_{vo}F_v}\begin{bmatrix} g_{in} & 0 \\ A_{vo} & r_{out}\end{bmatrix}=\frac{1}{1+A_{vo}F_v}\mathbf{g}_{Ao}$$

闭环放大器：输入电阻$\mathbf{r_{inf}}$增加，输出电阻$\mathbf{r_{outf}}$减小，电压增益$\mathbf{A_{vf}}$减小

单向化条件



双向网络传递函数

单向网络传递函数

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

输出回路
分压系数

本征
电压传递

输入回路
分压系数

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

单向化处理条件

闭环放大器视为单向网络的条件

$$\mathbf{g}_{AF} = \mathbf{h}_{AF}{}^{-1} = \frac{1}{1+A_{vo}F_v}\begin{bmatrix} g_{in} & -F_v g_{in} r_{out} \\ A_{vo} & r_{out} \end{bmatrix} \approx \frac{1}{1+A_{vo}F_v}\begin{bmatrix} g_{in} & 0 \\ A_{vo} & r_{out} \end{bmatrix} = \frac{1}{1+A_{vo}F_v}\mathbf{g}_{Ao}$$

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

$$\frac{A_{vo}}{1+A_{vo}F_v}\frac{F_v g_{in} r_{out}}{1+A_{vo}F_v} << \left(\frac{g_{in}}{1+A_{vo}F_v}+G_S\right)\left(\frac{r_{out}}{1+A_{vo}F_v}+R_L\right)$$

$$A_{v0}F_v g_{in} r_{out} \ll (g_{in}+(1+A_{v0}F_v)G_S)\,(r_{out}+(1+A_{v0}F_v)R_L)$$

$$A_{v0}F_v g_{in} r_{out} \ll g_{in}r_{out} + (1+A_{v0}F_v)R_L g_{in} + (1+A_{v0}F_v)G_S r_{out} + (1+A_{v0}F_v)G_S\,(1+A_{v0}F_v)R_L$$

$$A_{v0}F_v g_{in} r_{out} \ll (1+A_{v0}F_v)R_L g_{in} \approx A_{v0}F_v\, R_L g_{in}$$

$$A_{v0}F_v g_{in} r_{out} \ll (1+A_{v0}F_v)G_S r_{out} \approx A_{v0}F_v G_S r_{out}$$

$$A_{v0}F_v g_{in} r_{out} \ll (1+A_{v0}F_v)G_S\,(1+A_{v0}F_v)R_L \approx A_{v0}F_v\, A_{v0}F_v\, G_S R_L$$

$$R_L \gg r_{out}$$

$$R_S \ll r_{in}$$

$$\frac{R_L}{R_S} \gg \frac{1}{A_{v0}F_v}\frac{r_{out}}{r_{in}}$$

闭环放大器

$$R_L \gg r_{out}$$

$$R_S \ll r_{in}$$

$$\frac{R_L}{R_S} \gg \frac{1}{A_{v0}F_v}\frac{r_{out}}{r_{in}}$$

三个充分条件太容易满足，只管单向化处理即可

满足单向化条件：

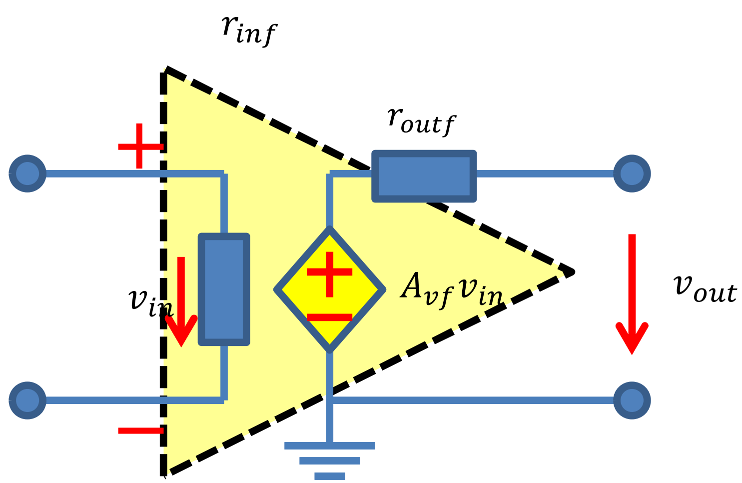
$$\mathbf{g}_{AF} \approx \frac{1}{1+A_{vo}F_v}\begin{bmatrix} g_{in} & 0 \\ A_{vo} & r_{out} \end{bmatrix} = \frac{1}{1+A_{vo}F_v}\mathbf{g}_{Ao}$$

$$r_{inf} = r_{in}(1+A_{vo}F_v)$$

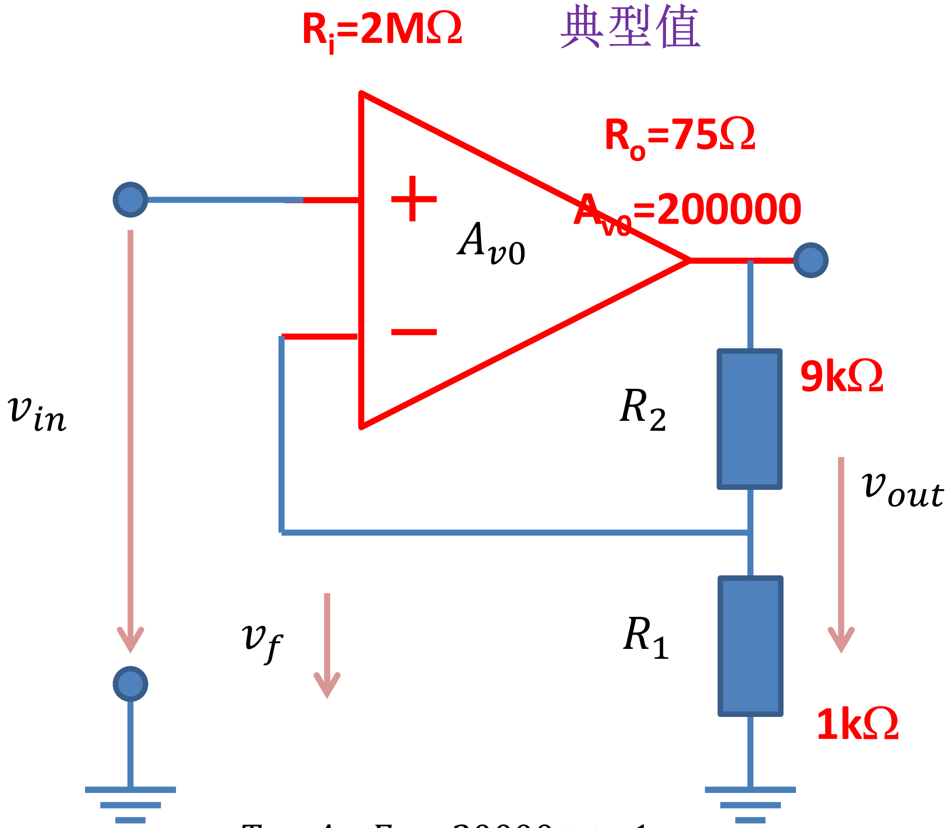
$$r_{outf} = \frac{r_{out}}{1+A_{vo}F_v}$$

$$A_{vf} = \frac{A_{vo}}{1+A_{vo}F_v} \approx \frac{1}{F_v}$$

深度负反馈条件



数值例



$$T = A_{v0}F_v = 20000 >> 1$$

$$\mathbf{h}_A = \begin{bmatrix} R_i & 0 \\ -A_{v0}R_iG_o & G_o \end{bmatrix} = \begin{bmatrix} 2M\Omega & 0 \\ -5.33\times10^9 & \frac{1}{75\Omega} \end{bmatrix}$$

$$\mathbf{h}_R = \begin{bmatrix} \frac{R_1R_2}{R_1+R_2} & \frac{R_1}{R_1+R_2} \\ -\frac{R_1}{R_1+R_2} & \frac{1}{R_1+R_2} \end{bmatrix} = \begin{bmatrix} 900\Omega & 0.1 \\ -0.1 & \frac{1}{10k\Omega} \end{bmatrix}$$

$$\mathbf{h}_{AF} = \mathbf{h}_A + \mathbf{h}_R \approx \begin{bmatrix} 2M\Omega & 0.1 \\ -5.33\times10^9 & \frac{1}{75\Omega} \end{bmatrix}$$

$$\mathbf{h}_{Ao} \approx \mathbf{h}_A$$

运放本身就是电压放大器，反馈网络的负载效应很弱，原始放大器可以直接视为开环放大器，电阻反馈网络只提供理想反馈系数

$$r_{inf} = r_{in}(1+T) = 40G\Omega$$

输入端可视为开路

$$r_{outf} = \frac{r_{out}}{1+T} = 0.0037\Omega$$

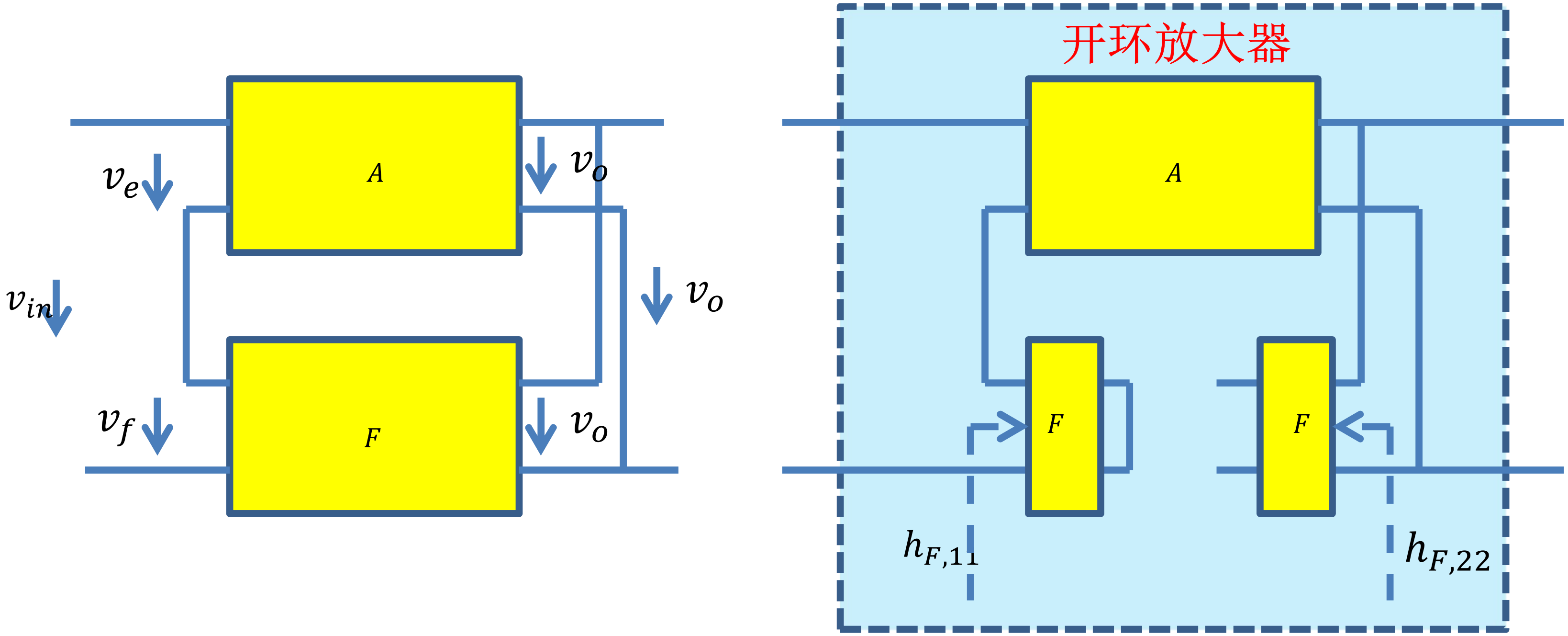
输出端内阻可视为0

$$A_{vf} = \frac{A_{v0}}{1+T} = 9.9995 \approx 10 = \frac{1}{F_v} = 1 + \frac{R_2}{R_1}$$

电压增益几乎等于反馈系数的倒数

该电路实现的是接近理想的压控压源，控制系数由反馈网络决定

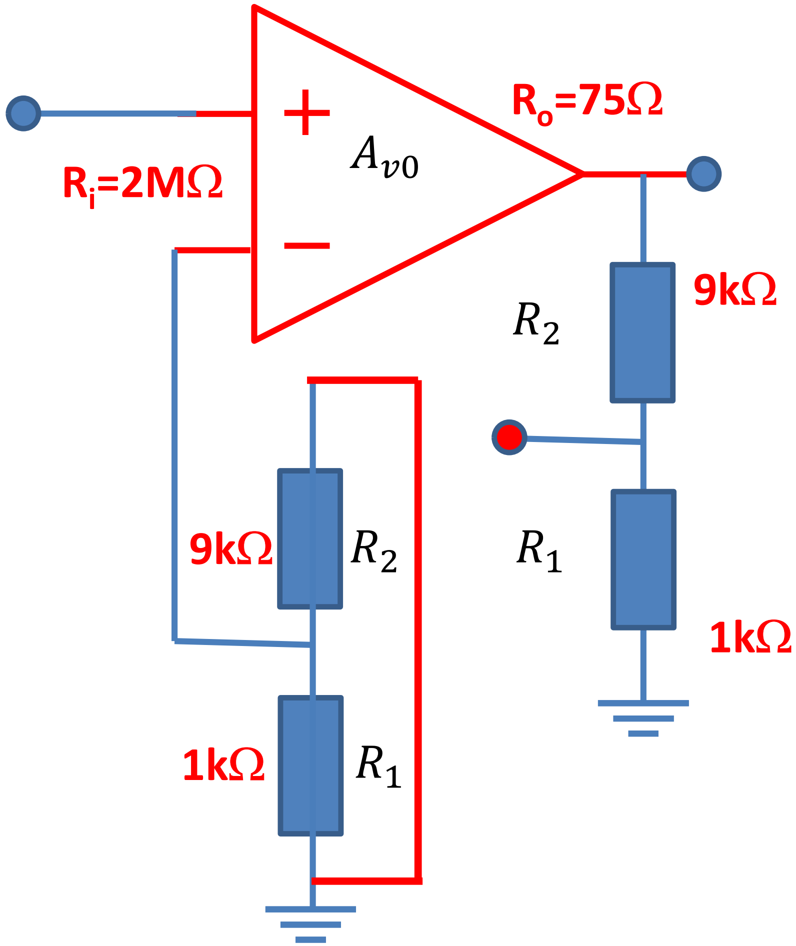
电路操作1

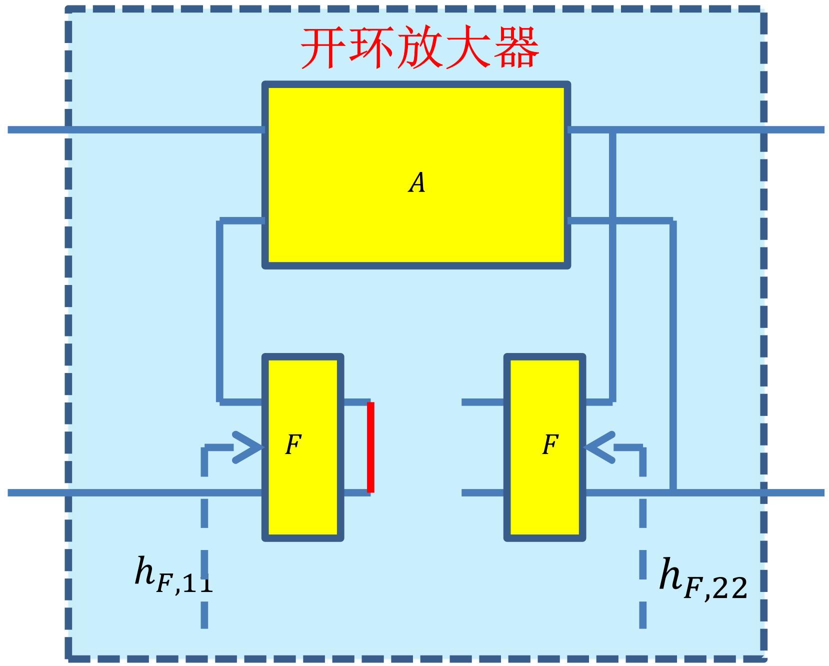


$$h = h_A + h_F = \begin{bmatrix} h_{A11} & 0 \\ h_{A21} & h_{A2} \end{bmatrix} + \begin{bmatrix} h_{F11} & h_{F1} \\ h_{F2} & h_{F22} \end{bmatrix} = \begin{bmatrix} h_{A11} + h_{F11} & 0 \\ h_{A21} + h_{F21} & h_{A22} + h_{F22} \end{bmatrix} + \begin{bmatrix} 0 & h_{F12} \\ 0 & 0 \end{bmatrix}$$

$$= h_{openloop,A} + h_{ideal,F} \approx \begin{bmatrix} h_{A11} + h_{F11} & 0 \\ h_{A21} & h_{A22} + h_{F22} \end{bmatrix} + \begin{bmatrix} 0 & h_{F12} \\ 0 & 0 \end{bmatrix}$$

开环放大器





$$r_{in} = r_{in,A} + r_{in,F} = 2M + 900 \approx 2M\Omega$$

$$g_{out} = g_{out,A} + g_{out,F} = \frac{1}{75} + \frac{1}{10k} \approx \frac{1}{75\Omega}$$

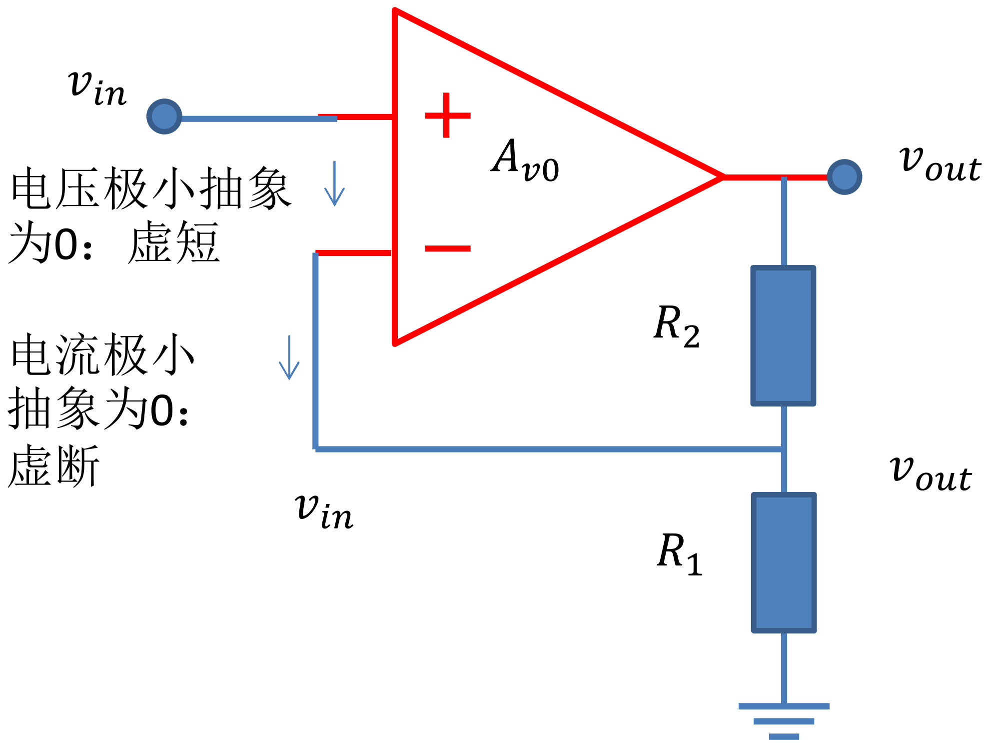
负载效应很微弱，开环放大器
参量几乎就是原始放大器参量

$$A_{v0} = \frac{r_{out,F}}{r_{out,A} + r_{out,F}} A_{v0,A} \frac{r_{in,A}}{r_{in,A} + r_{in,F}}$$

$$\approx A_{v0,A} = 200000$$

电路操作2：虚短虚断

- **T**实在太大了，无需考虑输入输出阻抗的影响（视其为**0**或无穷大），只考虑传输
- $\mathbf{A_{v0}}$实在太大了，输入电压和输入电流可视为**0**
  - 输入电压为**0**，虚短；输入电流为**0**，虚断



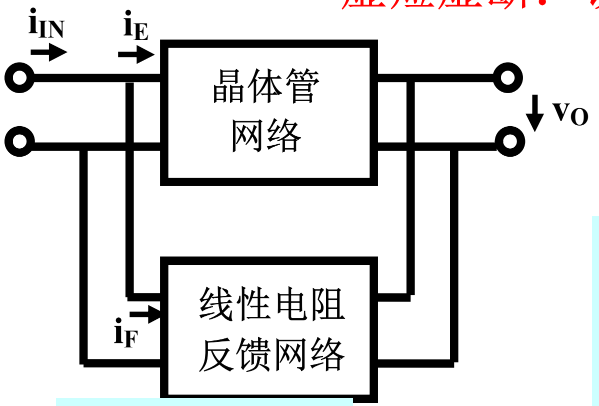
$$\frac{v_{in}}{R_1} = i_1 = \frac{v_{out} - v_{in}}{R_2}$$

$$v_{out} = \left(1 + \frac{R_2}{R_1}\right) v_{in} = \left(1 + \frac{9}{1}\right) v_{in} = 10 v_{in}$$

高增益放大器，深度负反馈
闭环增益的一般性结论

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

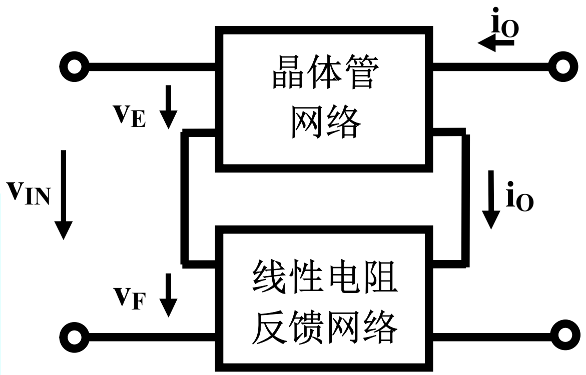
虚短虚断：误差电压电流为0：无穷大增益



$$R_{mf} = \frac{1}{F} = \frac{1}{G_F}$$

并并负反馈

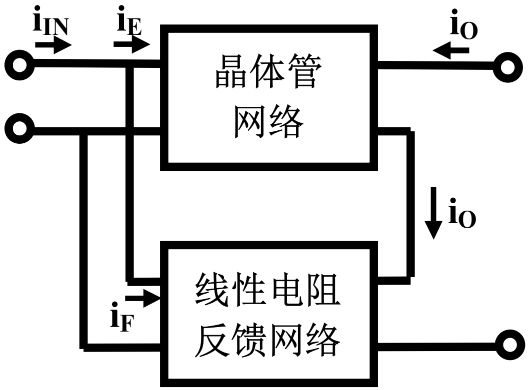
$$F = \frac{i_F}{v_O} = \frac{短路电流}{激励电压} = G_F$$



$$G_{mf} = \frac{1}{F} = \frac{1}{R_F}$$

串串负反馈

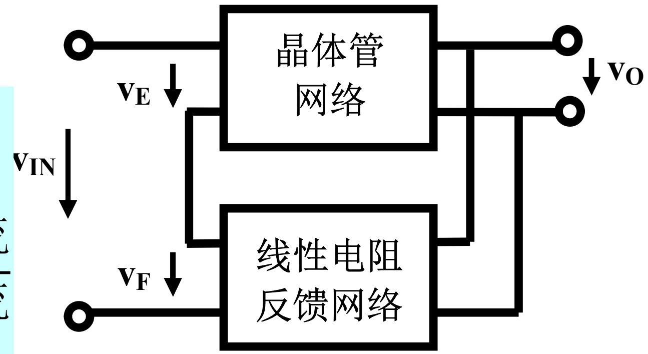
$$F = \frac{v_F}{i_O} = \frac{开路电压}{激励电流} = R_F$$



并串负反馈

$$A_{if} = \frac{1}{F} = \frac{1}{F_i}$$

$$F = \frac{i_F}{i_O} = \frac{短路电流}{激励电流} = F_i$$



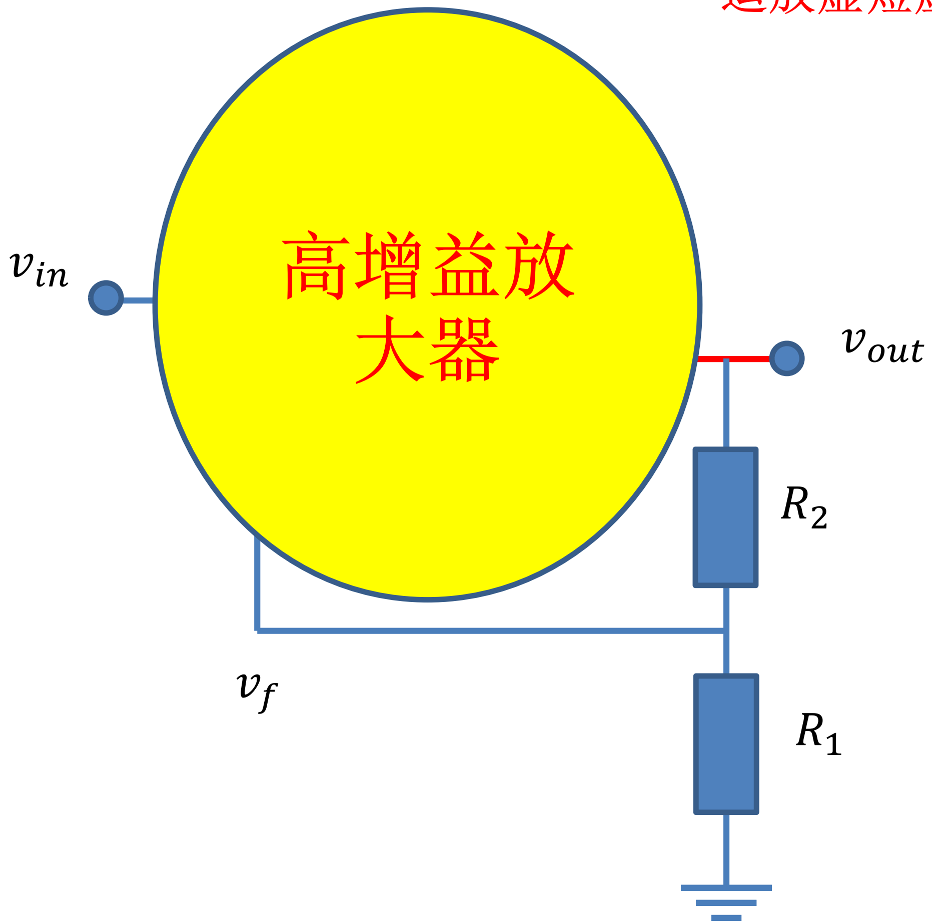
串并负反馈

$$A_{vf} = \frac{1}{F} = \frac{1}{F_v}$$

$$F = \frac{v_F}{v_O} = \frac{开路电压}{激励电压} = F_v$$

串并连接
检测输出电压，形成反馈电压

运放虚短虚断分析，非运放反馈系数分析



$$F = \frac{v_f}{v_o} = \frac{开路电压}{激励电压} = \frac{R_1}{R_1 + R_2} = F_v$$

$$A_{vf} = \frac{1}{F_v} = 1 + \frac{R_2}{R_1}$$

实用的负反馈放大器，只需确认连接关系，
由反馈系数直接获得闭环增益

设计例 例**3.11.4**

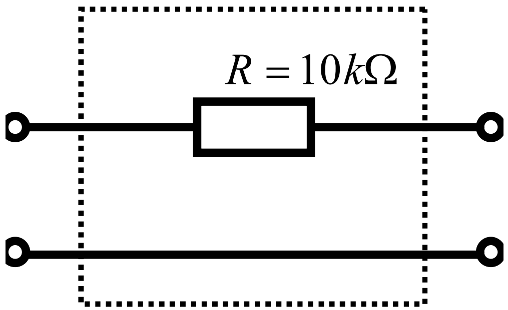
- 请设计一个跨阻增益为**10kΩ**的跨阻器以实现线性流压转换，分析其输入电阻、输出电阻大小。

- 可选用材料：**741**运算放大器（输入电阻**2MΩ**，输出电阻**75Ω**，电压增益**20000~200000**不确定，该电压放大器输出端口的下端点为参考地）一个，线性电阻若干。

设计考虑

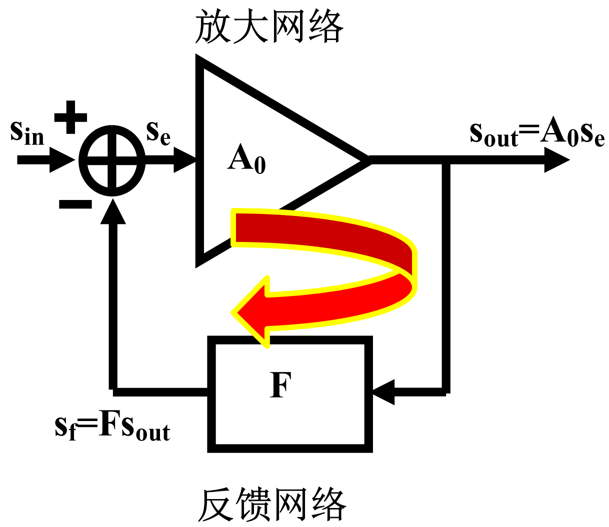
- 跨阻器：线性流压转换器，接近于理想的流控压源
- 利用负反馈实现接近理想的受控源
  - 只要深度负反馈，即可实现接近理想的受控源
  - 深度负反馈由运放的高电压增益保证
- 利用并并负反馈实现接近理想的流控压源
  - 只要深度负反馈，闭环增益近似等于反馈系数倒数
  - **10kΩ**跨阻增益**----0.1mS**的跨导反馈系数

如何实现0.1mS的跨导反馈



$$\mathbf{y}_F = \begin{bmatrix} G & -G \\ -G & G \end{bmatrix}$$

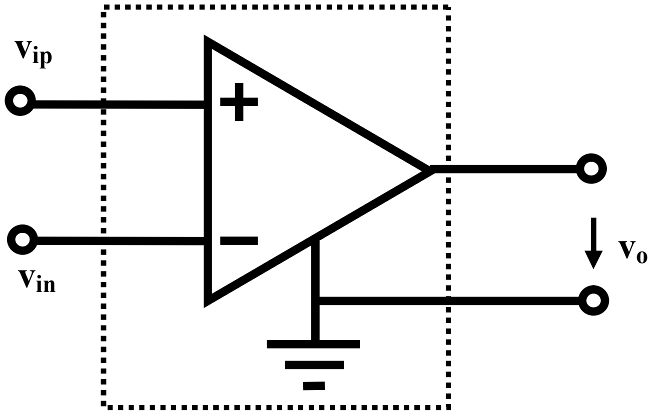
10kΩ串臂电阻可实现
0.1mS跨导反馈系数



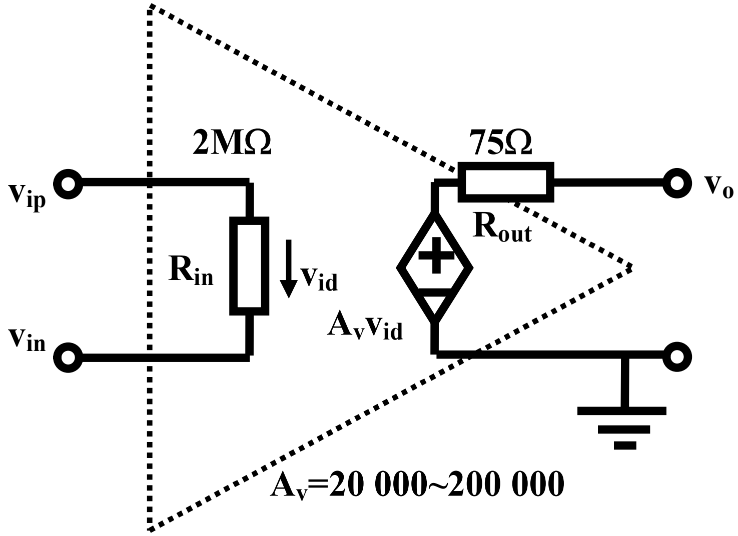
放大网络提供端口**1**到
端口**2**的开环增益

反馈网络提供端口**2**到
端口**1**的反馈系数

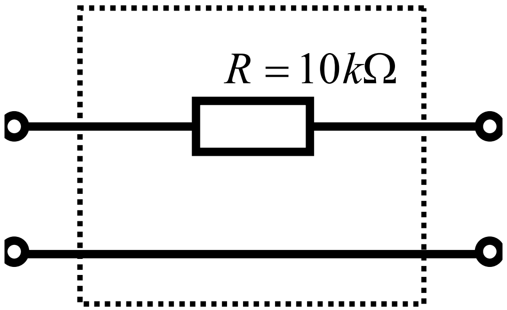
放大网络和反馈网络



vip
vin
vo

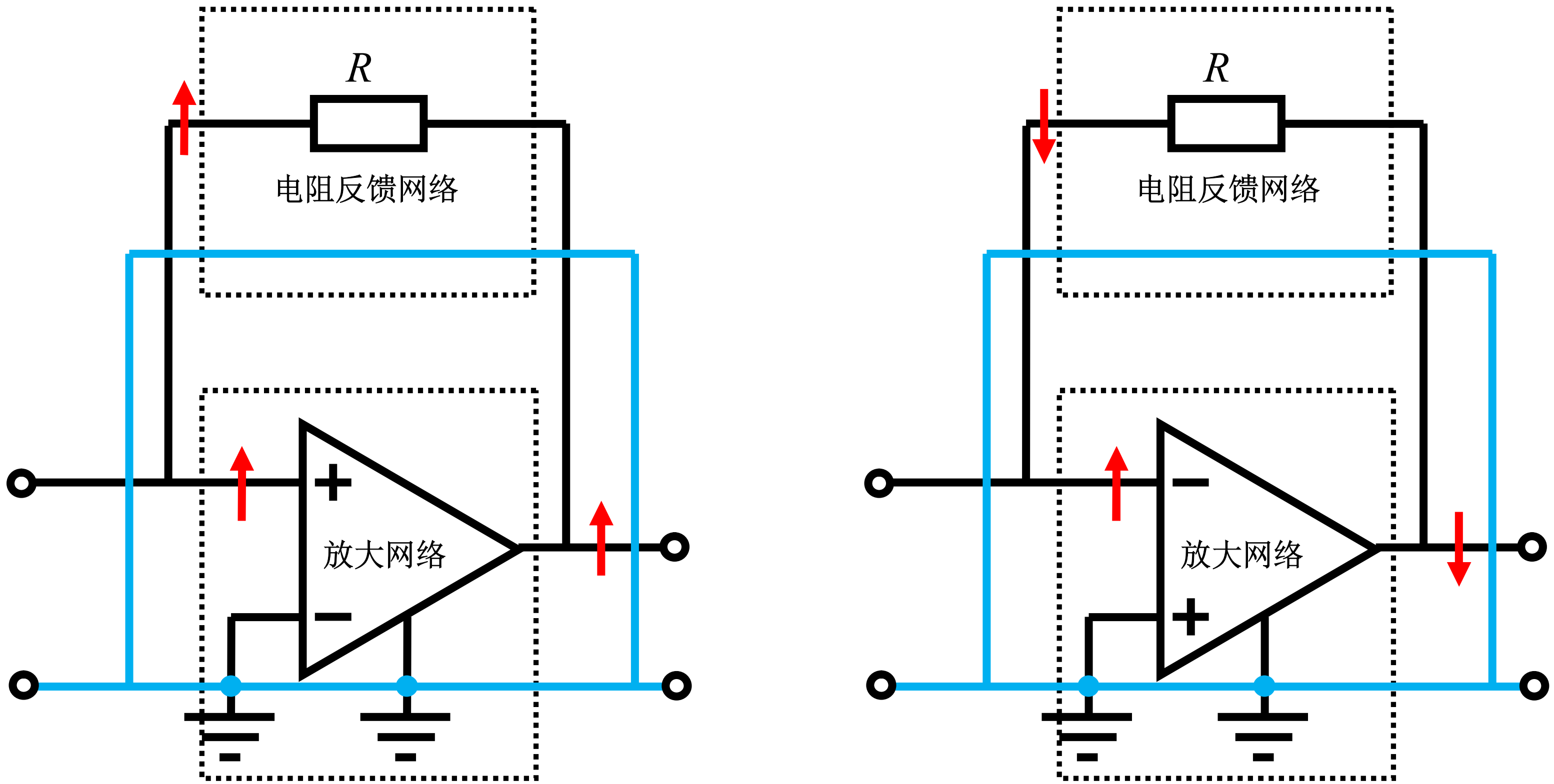


2MΩ
75Ω
vip
vo
Rout
Rin
vid
Avvid
vin
Av=20 000~200 000

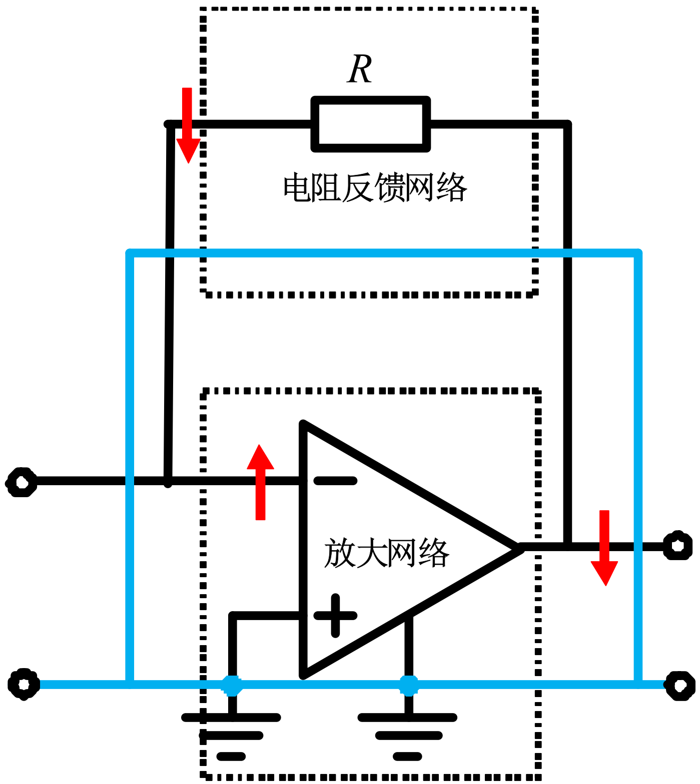


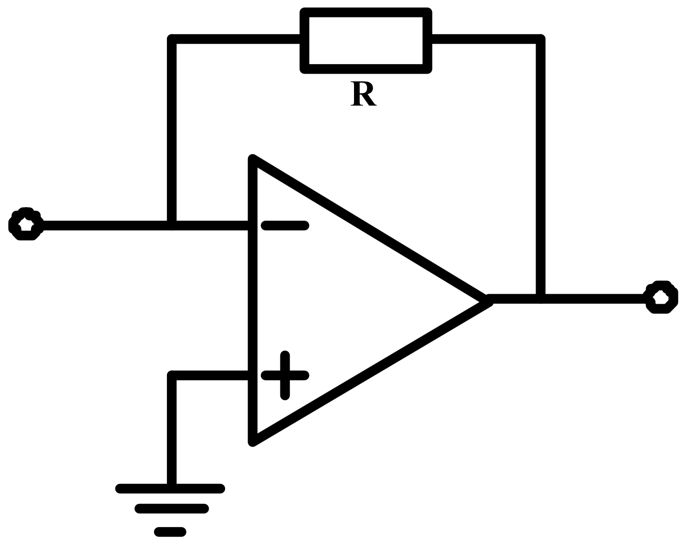
R = 10kΩ

负反馈连接

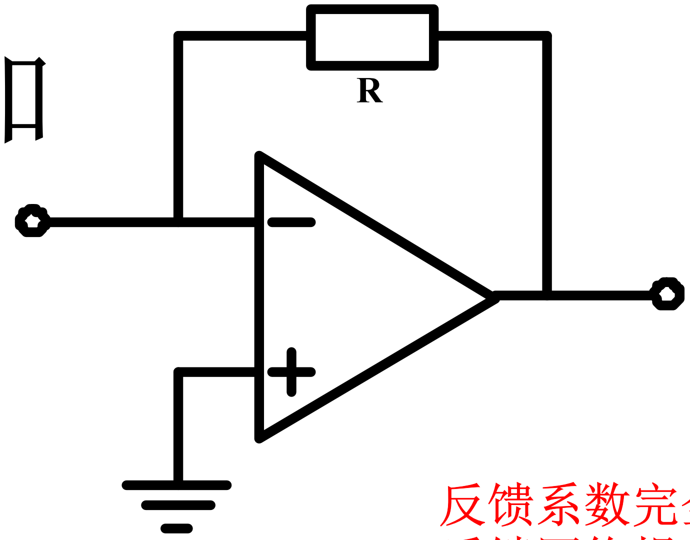


设计结果





验证：并并连接y相加



$$\mathbf{y}_A = \begin{bmatrix} G_{in} & 0 \\ A_v G_{out} & G_{out} \end{bmatrix} = \begin{bmatrix} 0.5\mu S & 0 \\ 2667S & 13.3mS \end{bmatrix}$$

$$\mathbf{y}_F = \begin{bmatrix} G & -G \\ -G & G \end{bmatrix} = \begin{bmatrix} 0.1mS & -0.1mS \\ -0.1mS & 0.1mS \end{bmatrix}$$

反馈系数完全由
反馈网络提供

流控压源和压控压源
输入端要求不一致
输入端口负载效应强

$$\mathbf{y}_{AF} = \mathbf{y}_A + \mathbf{y}_F = \begin{bmatrix} G_{in} + G & -G \\ A_v G_{out} - G & G_{out} + G \end{bmatrix} = \begin{bmatrix} 0.1005mS & -0.1mS \\ 2667S & 13.4mS \end{bmatrix}$$

反馈网络提供的前向增益无法和放大网络比，可以忽略

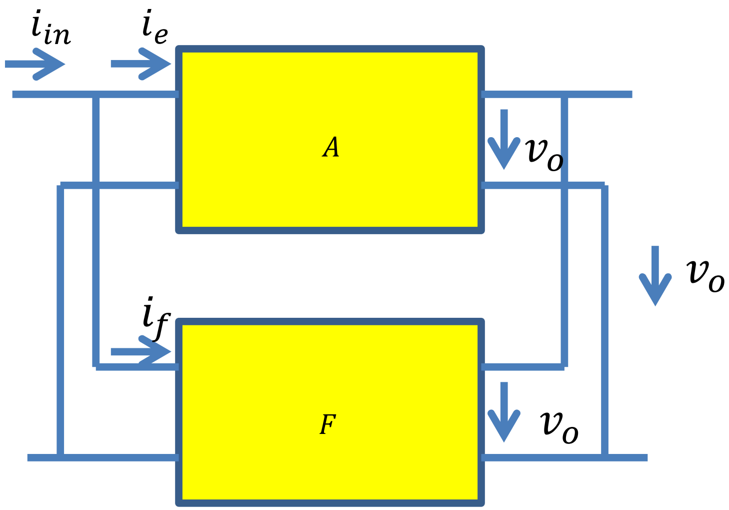
流控压源和压控压源
输出端要求一致
输出端口负载效应弱

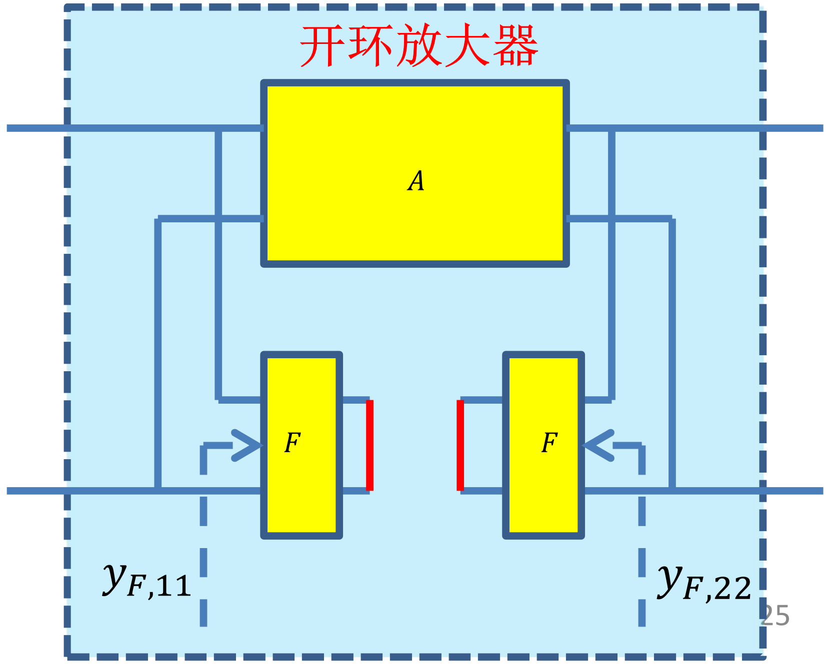
分解为开环放大器和理想反馈网络

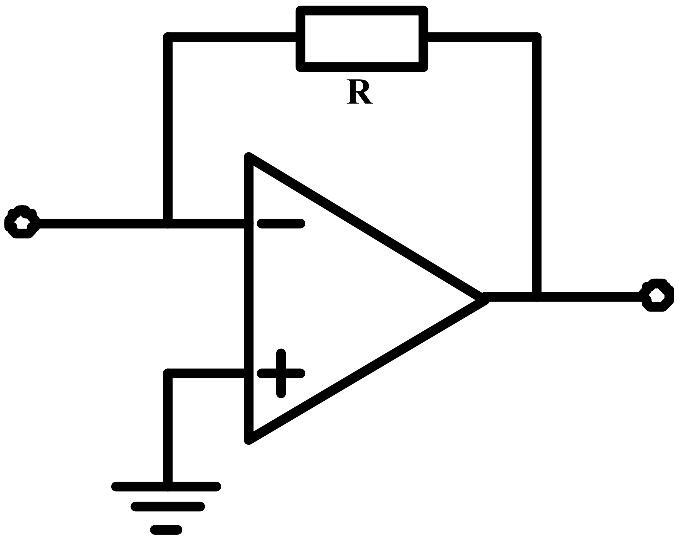
$$\mathbf{y}_{AF}=\begin{bmatrix} G_{in}+G & 0 \\ A_vG_{out}-G & G_{out}+G \end{bmatrix}+\begin{bmatrix} 0 & -G \\ 0 & 0 \end{bmatrix}$$
$$=\begin{bmatrix} 0.1005mS & 0 \\ 2667S & 13.4mS \end{bmatrix}+\begin{bmatrix} 0 & -0.1mS \\ 0 & 0 \end{bmatrix}$$
$$=\mathbf{y}_{OpenLoop,A}+\mathbf{y}_{Ideal,F}=\begin{bmatrix} g_{in} & 0 \\ -R_{m0}g_{in}g_{out} & g_{out} \end{bmatrix}+\begin{bmatrix} 0 & G_F \\ 0 & 0 \end{bmatrix}$$

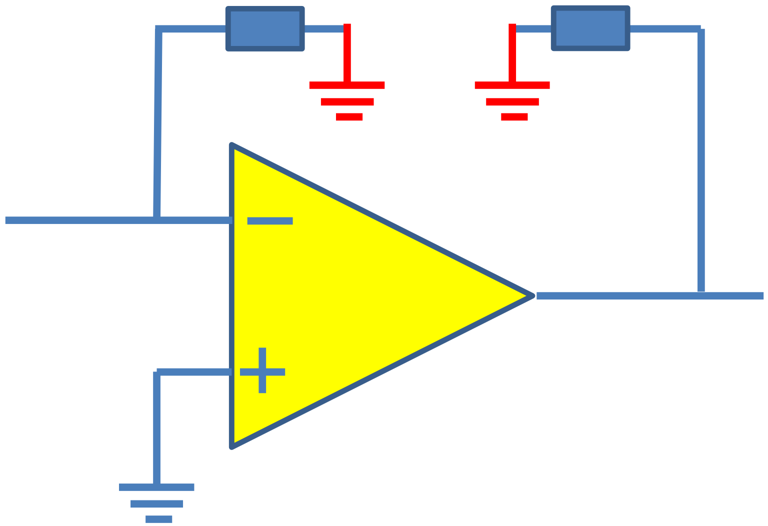
$$\mathbf{z}_{OpenLoop,A}=\mathbf{y}_{OpenLoop,A}^{-1}=\begin{bmatrix} 0.1005mS & 0 \\ 2667S & 13.4mS \end{bmatrix}^{-1}=\begin{bmatrix} 9.95k\Omega & 0 \\ -1.975G\Omega & 74.44\Omega \end{bmatrix}=\begin{bmatrix} r_{in} & 0 \\ R_{m0} & r_{out} \end{bmatrix}$$

开环放大器





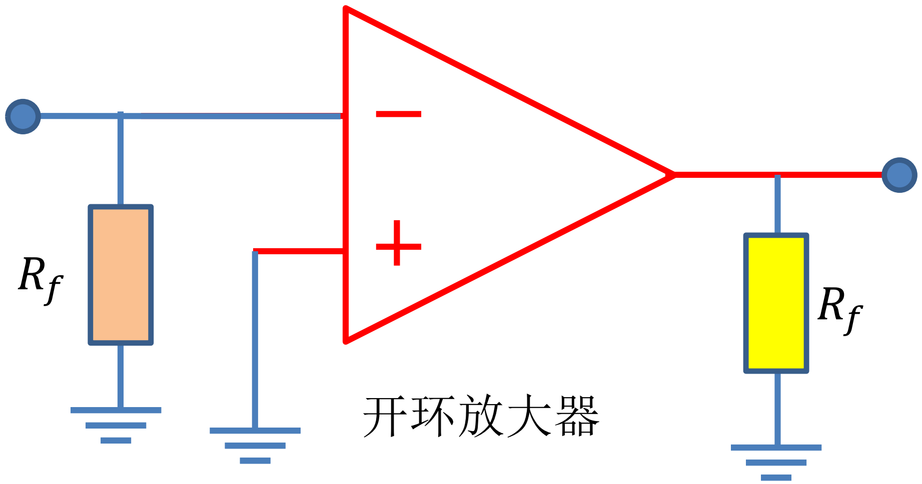




开环放大器参量

$$r_{in0} = R_{in}||R_f = 2M||10k = 9.95k\Omega$$

本例中，负反馈网络在输入端的负载效应强烈，闭环放大器输入电阻几乎由负反馈网络决定



$$r_{out0} = R_{out}||R_f = 75\Omega||10k = 74.44\Omega$$

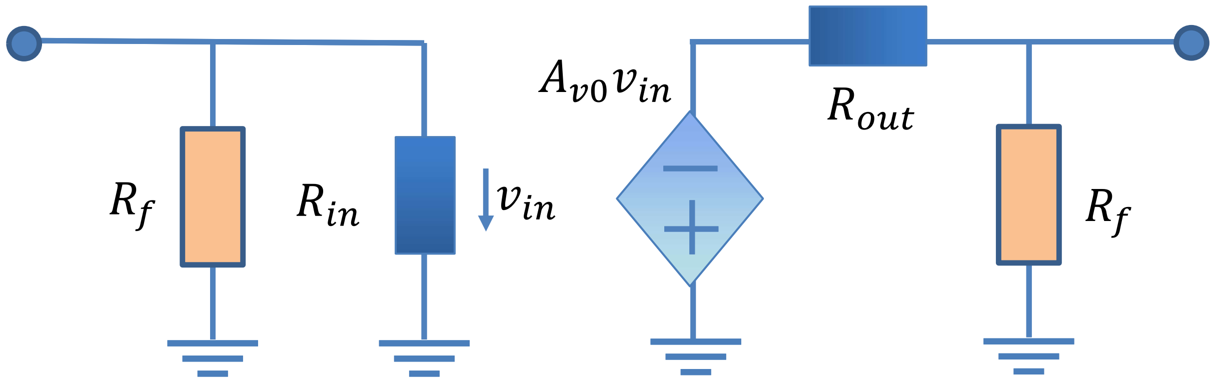
本例中，负反馈网络在输出端的负载效应微弱，闭环放大器输出电阻几乎就是原始放大器输出电阻

$$R_{m0} = \frac{v_{out,open}}{i_{in}}$$

$$= \frac{v_{out,open}}{v_{in}}\frac{v_{in}}{i_{in}}$$

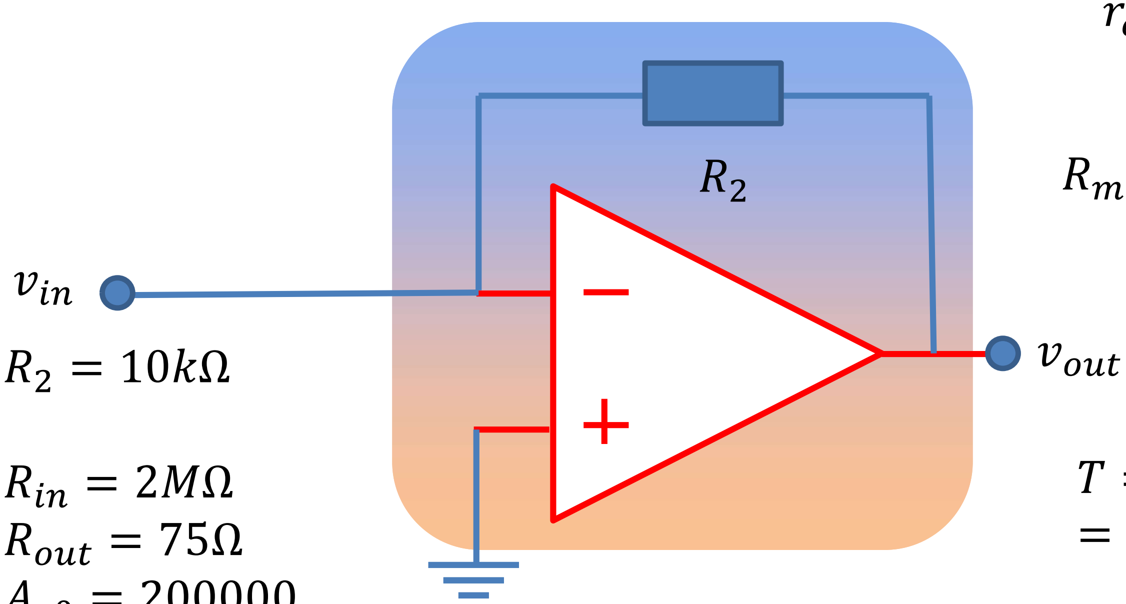
$$= -A_{v0}\frac{R_f}{R_{out}+R_f}r_{in0}$$

$$= -1.975G\Omega$$



极大的开环增益可使得深度负反馈条件极易满足

闭环放大器参量



$R_2 = 10k\Omega$

$R_{in} = 2M\Omega$
$R_{out} = 75\Omega$
$A_{v0} = 200000$

$$r_{in0} = R_{in}||R_2 = 2M||10k = 9.95k\Omega$$

$$r_{out0} = R_{out}||R_2 = 75||10k = 74.44\Omega$$

$$R_{m0} = -A_{v0}\frac{R_2}{R_{out} + R_2}r_{in0} = -1.975G\Omega$$

$$G_F = -\frac{1}{R_2} = -0.1mS$$

$$T = R_{m0}G_F = (-1.975G\Omega) \times (-0.1mS) = 19.75 \times 10^4 \gg 1$$

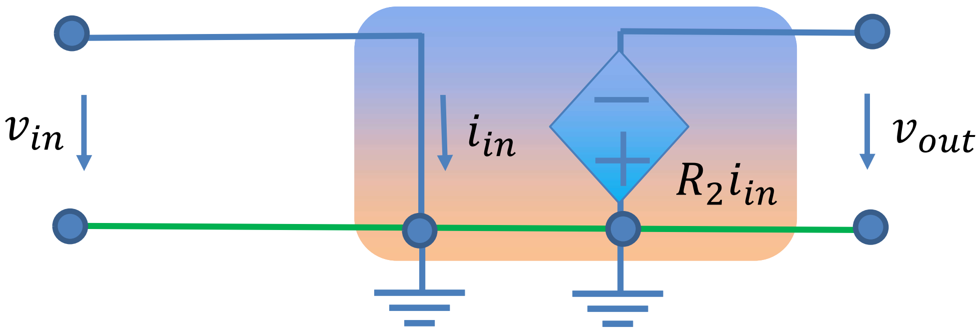
深度负反馈可使得负反馈放大器接近理想流控压源

$$r_{inf} = \frac{r_{in0}}{1 + T} = 50m\Omega \approx 0\Omega$$

$$r_{outf} = \frac{r_{out0}}{1 + T} = 0.38m\Omega \approx 0\Omega$$

$$R_{mf} = \frac{R_{m0}}{1 + T} = -9.999k\Omega \approx -10k\Omega = -R_2$$

$m\Omega$量级r_{inf}、r_{outf}被视为短路



反相电压放大器等效电路

闭环放大器接近理想流控压源

$$\mathbf{z}_{AF} = \mathbf{y}_{AF}^{-1} = \begin{bmatrix} g_{in} & G_F \\ -R_{m0} g_{in} g_{out} & g_{out} \end{bmatrix}^{-1} = \begin{bmatrix} 0.1005mS & -0.1mS \\ 2667S & 13.4mS \end{bmatrix}^{-1}$$

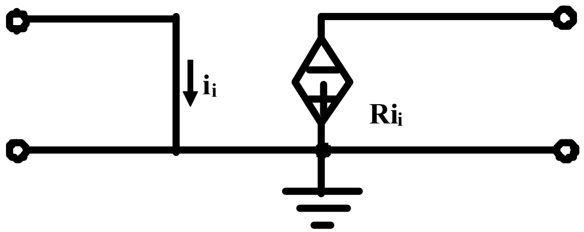
$$= \begin{bmatrix} 50.4m\Omega & 0.375m\Omega \\ -9.999949k\Omega & 0.377m\Omega \end{bmatrix}$$

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

$$3.75 << |(R_S + 0.0504)(R_L + 0.000377)|$$

$$\mathbf{z}_{AF} = \begin{bmatrix} 50.4m\Omega & 0.375m\Omega \\ -9.999949k\Omega & 0.377m\Omega \end{bmatrix} \approx \begin{bmatrix} 50.4m\Omega & 0 \\ -9.999949k\Omega & 0.377m\Omega \end{bmatrix}$$

输入电阻：**50.4mΩ**极小，视同短路
输出电阻：**0.377mΩ**极小，视同短路
跨阻增益：**10kΩ（-5ppm）**，十分稳定



练习

- 请设计一个电流放大器，其电流增益为**10**，要求它足够接近于理想流控流源。

- 可选用材料：**741**运算放大器一个，线性电阻若干。

晶体管负反馈放大器分析例

- 用级联方式获得高增益和深度负反馈
- **cascade**：级联：一级接一级地放大
  - 提高增益 $A = A_1 A_2 \ldots A_n$
  - 有足够高的增益后，采用负反馈，用线性负反馈电阻网络来获得稳定的线性放大增益
  - 以**MC1552**为例说明

$$AF >> 1$$

增益**A**可能是电压增益、电流增益，跨导增益，跨阻增益

$$A_F = \frac{A}{1 + AF} \approx \frac{1}{F}$$

MC1552G
MC1553G

ORDERING INFORMATION

Device	Temperature Range	Package
MC1552G	−55°C to +125°C	Metal Can
MC1553G	−55°C to +125°C	Metal Can

HIGH FREQUENCY VIDEO AMPLIFIER

SILICON MONOLITHIC INTEGRATED CIRCUIT

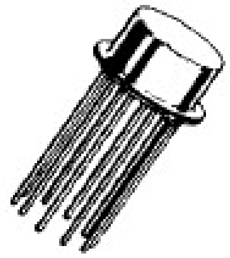
VIDEO AMPLIFIERS

These devices consist of a three-stage, direct-coupled, common-emitter cascade incorporating series feedback to achieve stable voltage gain, low distortion, and wide bandwidth. They employ a temperature-compensated dc feedback loop to stabilize the operating point and a current-biased emitter follower output and are intended for use as either wide-band linear amplifiers or as fast rise pulse amplifiers.

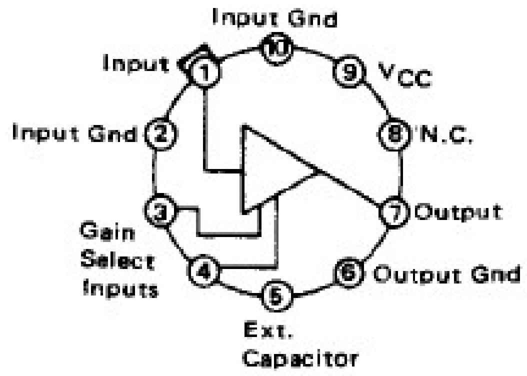
三级共射组态级联，直接耦合，串联负反馈：稳定电压增益，低失真，宽带

- High Gain — 34 dB ± 1 dB (MC1552)
  52 dB ± 1 dB (MC1553)
- Wide Bandwidth — 40 MHz (MC1552)
  35 MHz (MC1553)
- Low Distortion — 0.2% at 200 kHz
- Low Temperature Drift — ±0.002 dB/°C

CASE 603B
METAL PACKAGE



PIN CONNECTIONS



原理图，额定值

FIGURE 1 – MC1552 (LOW GAIN)

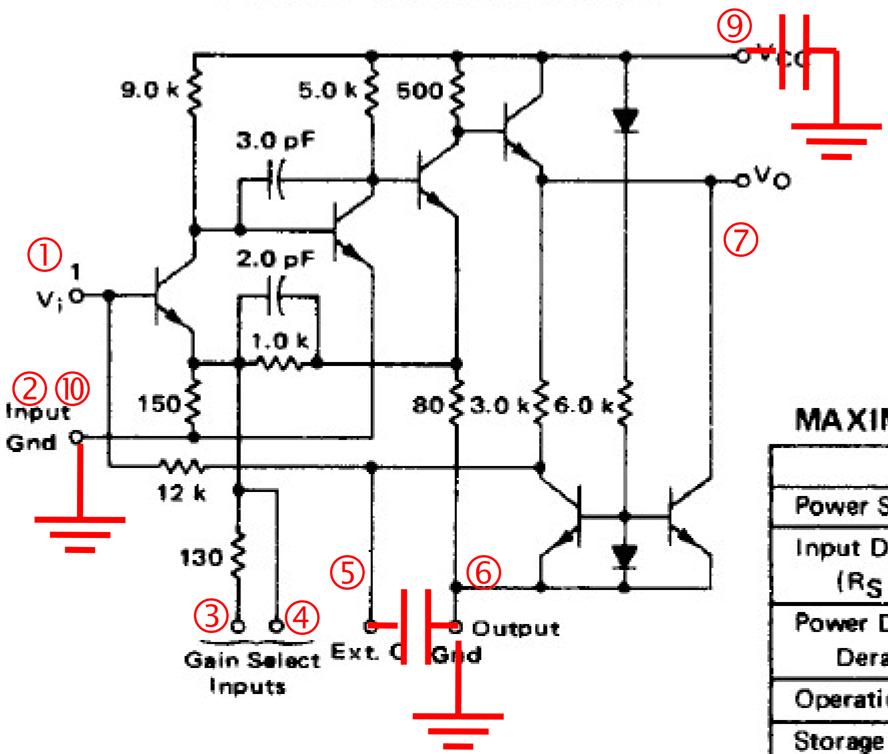
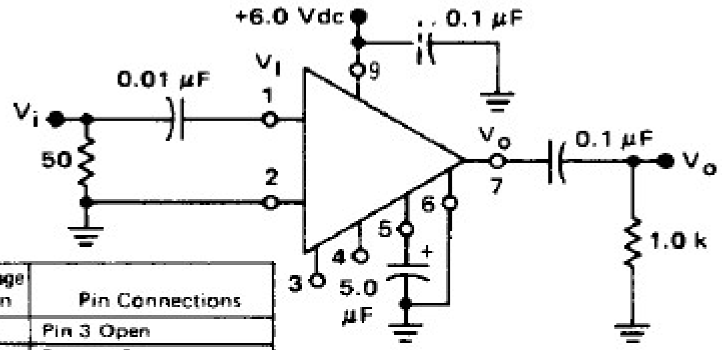


FIGURE 3 – TEST CIRCUIT



Type	Voltage Gain	Pin Connections
MC1552	50	Pin 3 Open
	100	Ground Pin 3

MAXIMUM RATINGS (T_A = +25°C unless otherwise noted.)

Rating	Symbol	Value	Unit
Power Supply Voltage, Pin 9	V_{CC}	9.0	Vdc
Input Differential Voltage, Pin 1 to Pin 2 (R_S = 500 ohms)	V_{ID}	1.0	V(rms)
Power Dissipation (Package Limitation) Derate above T_A = +25°C	P_D	680 4.6	mW mW/°C
Operating Ambient Temperature Range	T_A	-55 to +125	°C
Storage Temperature Range	T_{stg}	-65 to +150	°C

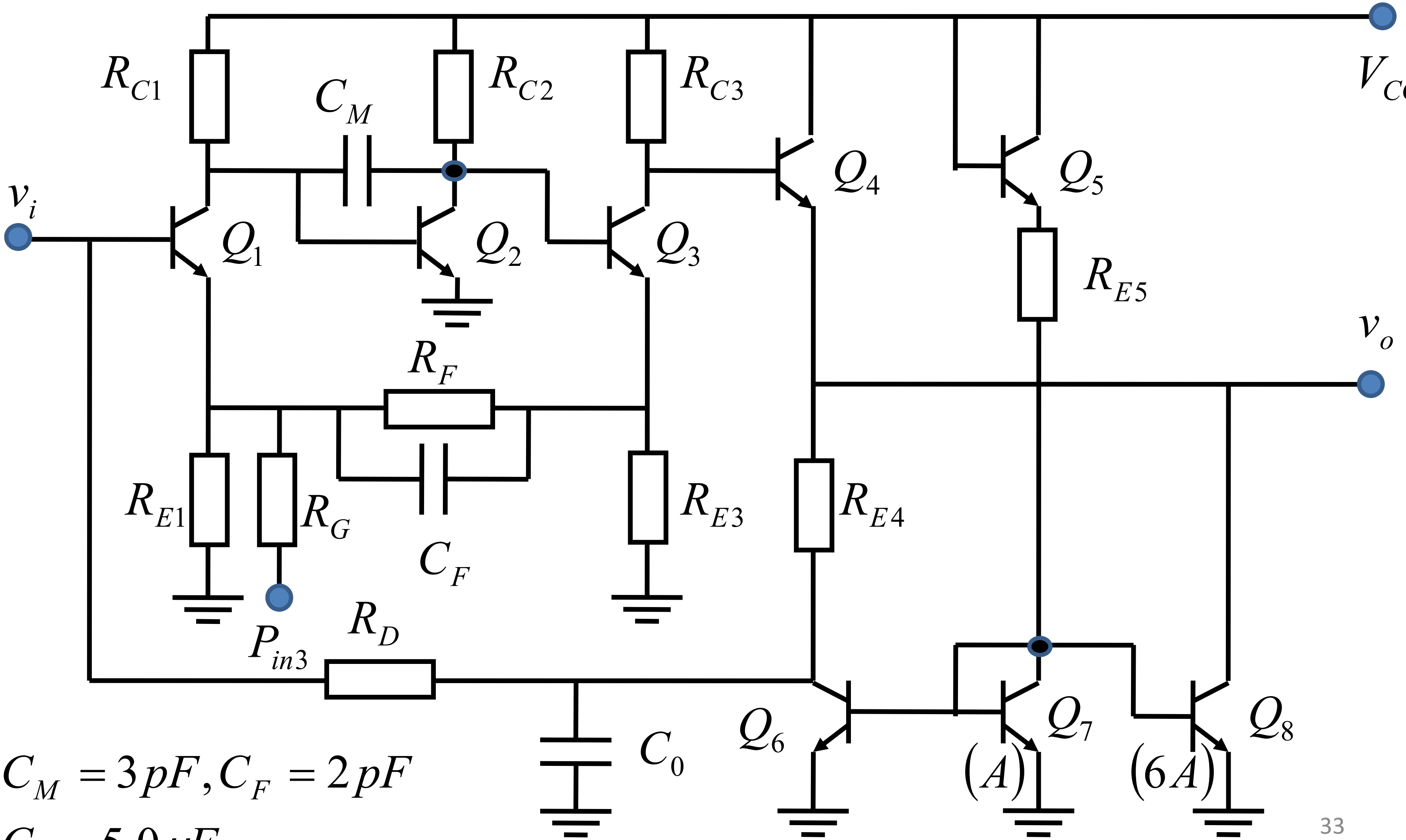
增益测试

$A_v = 50$

$V_{CC} = 6V \quad R_{C1} = 9.0k\Omega, R_{C2} = 5.0k\Omega, R_{C3} = 500\Omega$

$R_{E1} = 150\Omega, R_F = 1.0k\Omega, R_{E3} = 80\Omega$

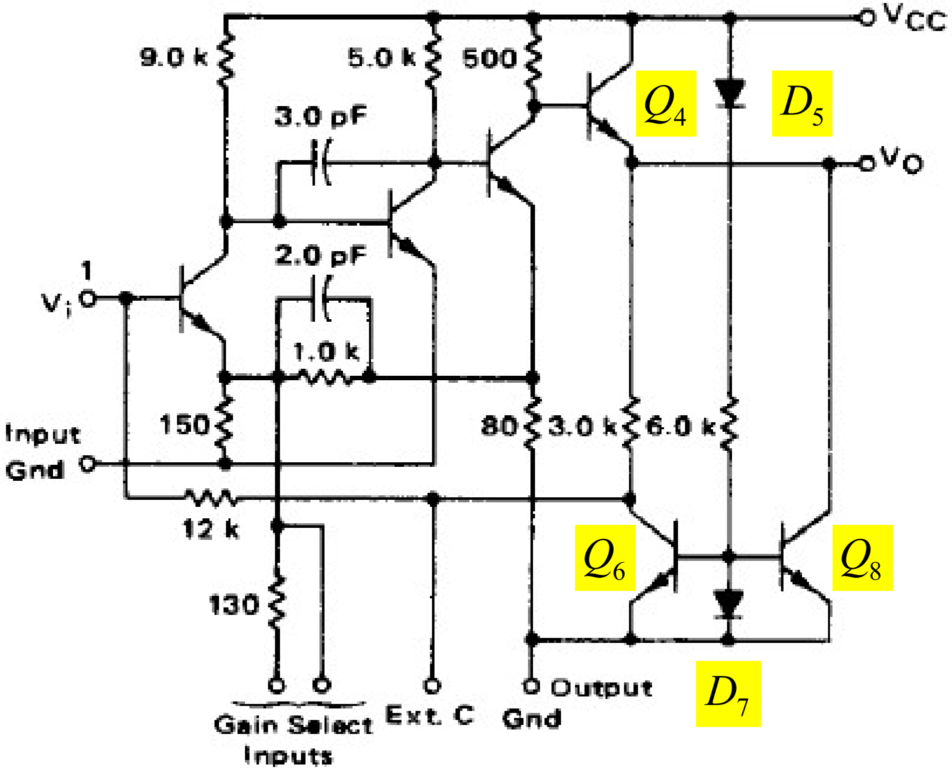
$R_G = 130\Omega \qquad R_{E4} = 3.0k\Omega, R_{E5} = 6.0k\Omega, R_D = 12k\Omega$

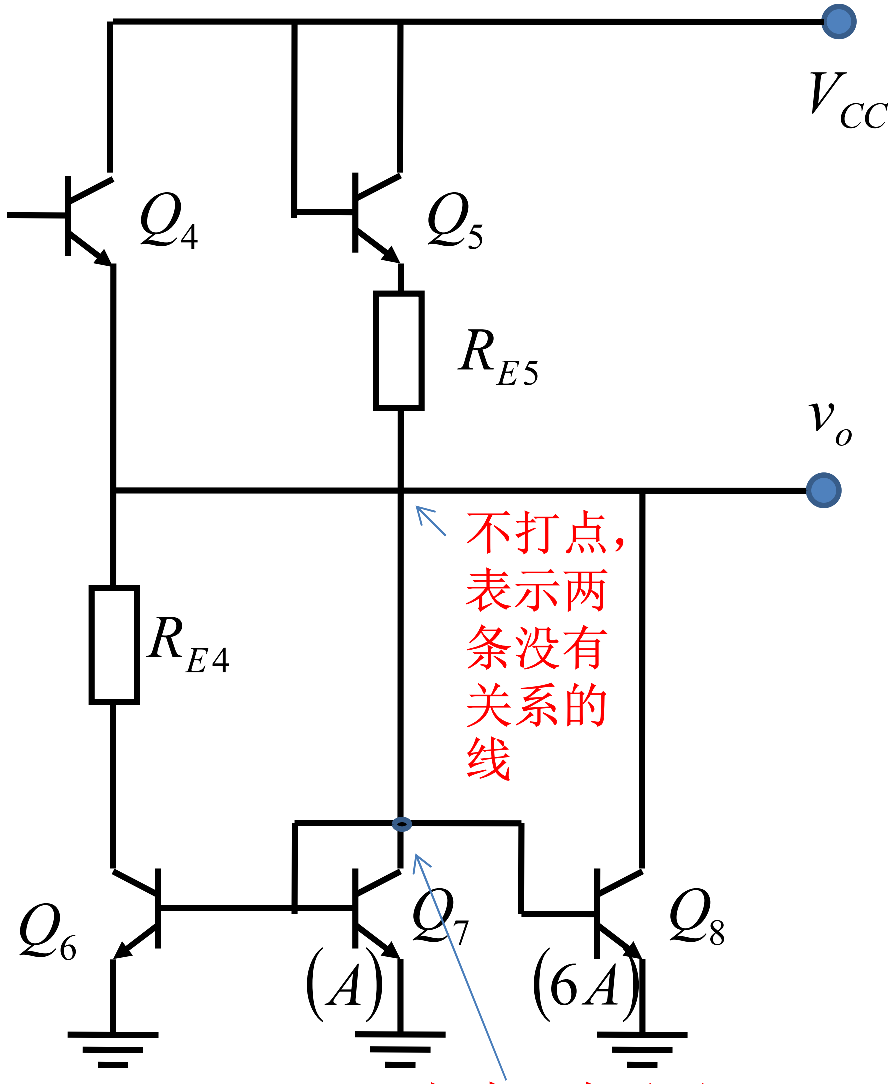


$C_M = 3pF, C_F = 2pF$

$C_0 = 5.0\mu F$

偏置参考源





打点，表示两
条线连通：一
个结点

参考电流

$$I_{E5} = \frac{V_{CC} - V_{BE5} - V_{BE7}}{R_{E5}}$$

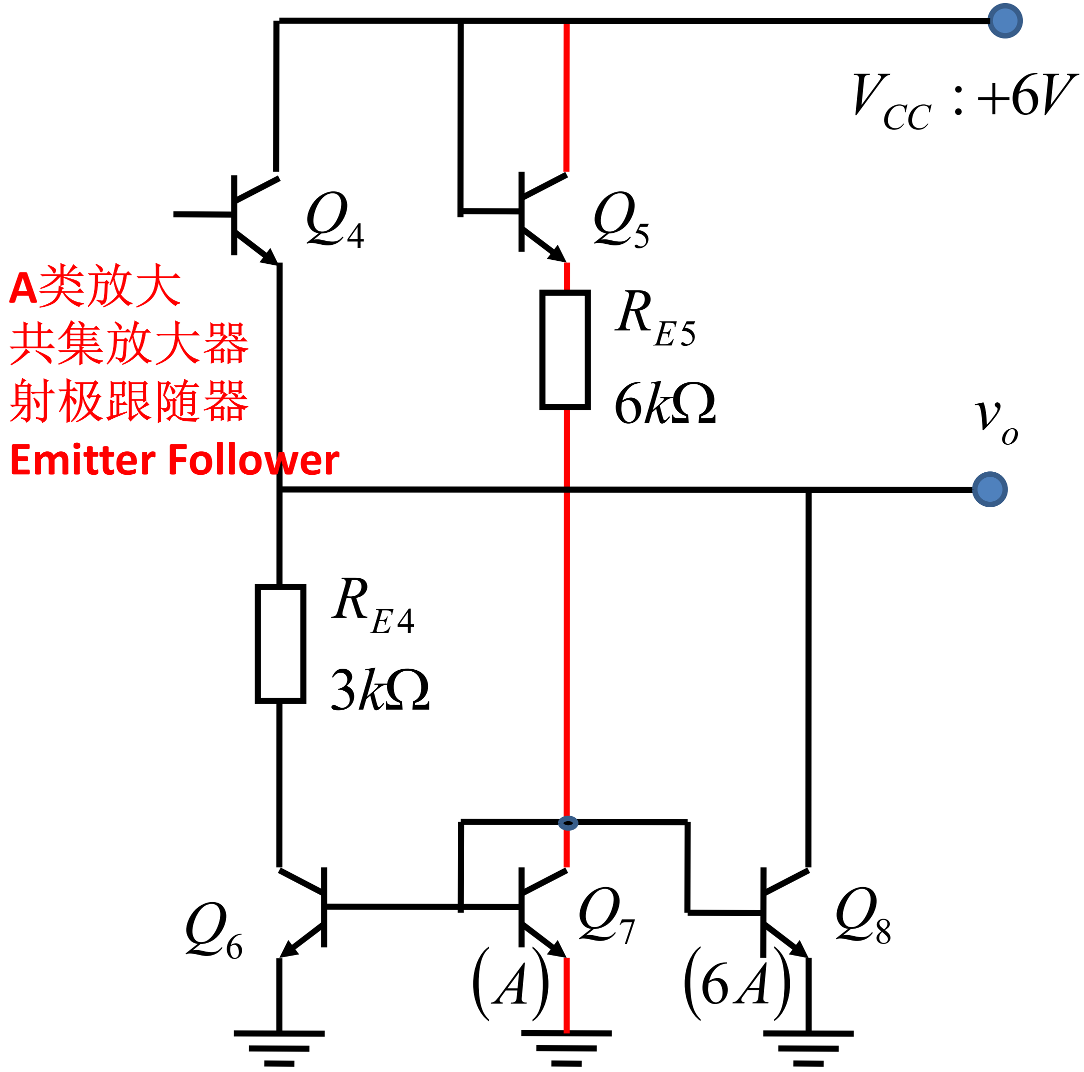
$$= \frac{6 - 0.7 - 0.7}{6k} = 0.77mA$$

$$I_{E6} = I_{E7} = I_{E5} = 0.77mA$$

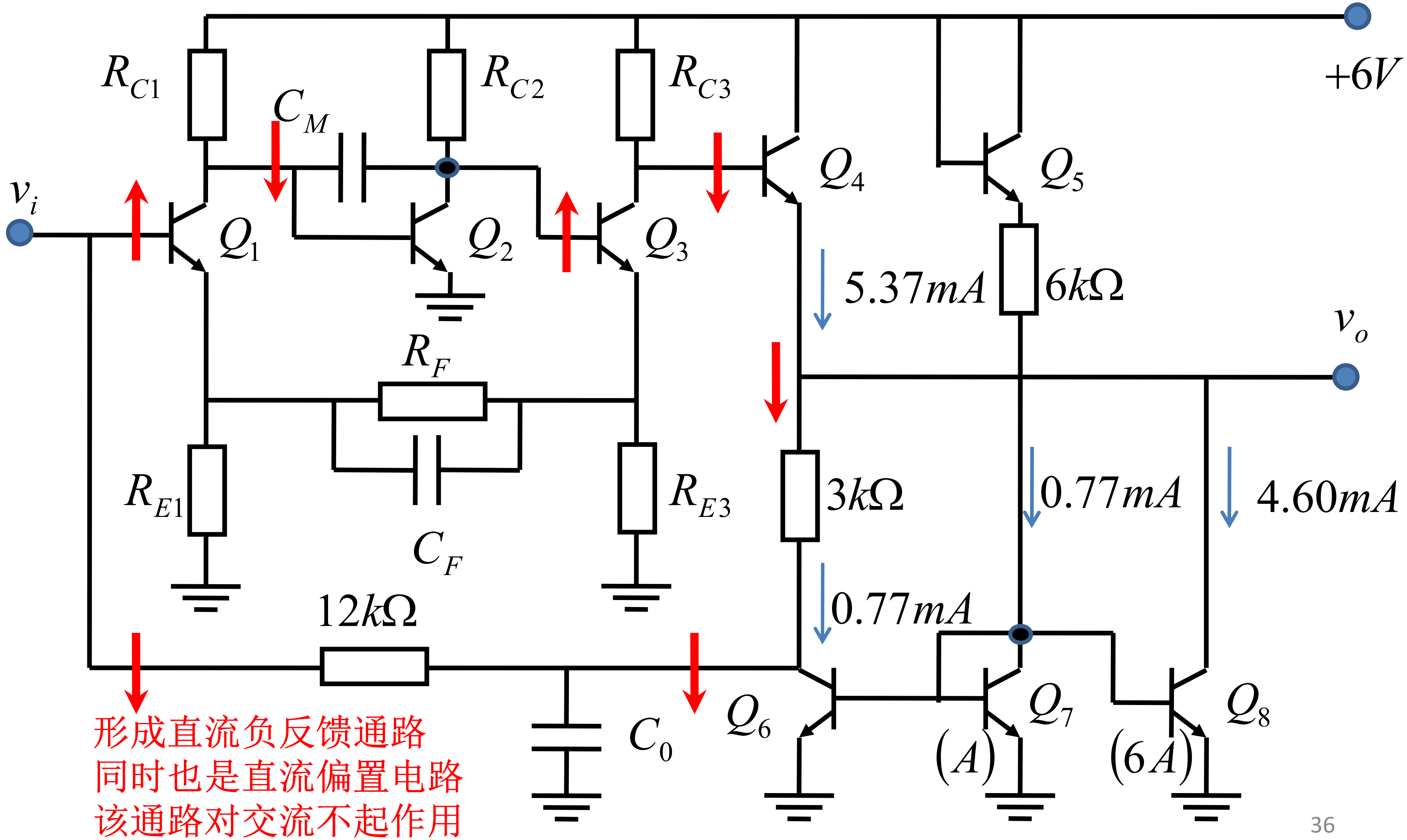
$$I_{E8} = 6I_{E7} = 4.60mA$$

$$I_{E4} = I_{C6} + I_{C8} \approx 5.37mA$$

$$V_{R_{E4}} = I_{C6}R_{E4} \approx 2.30V$$

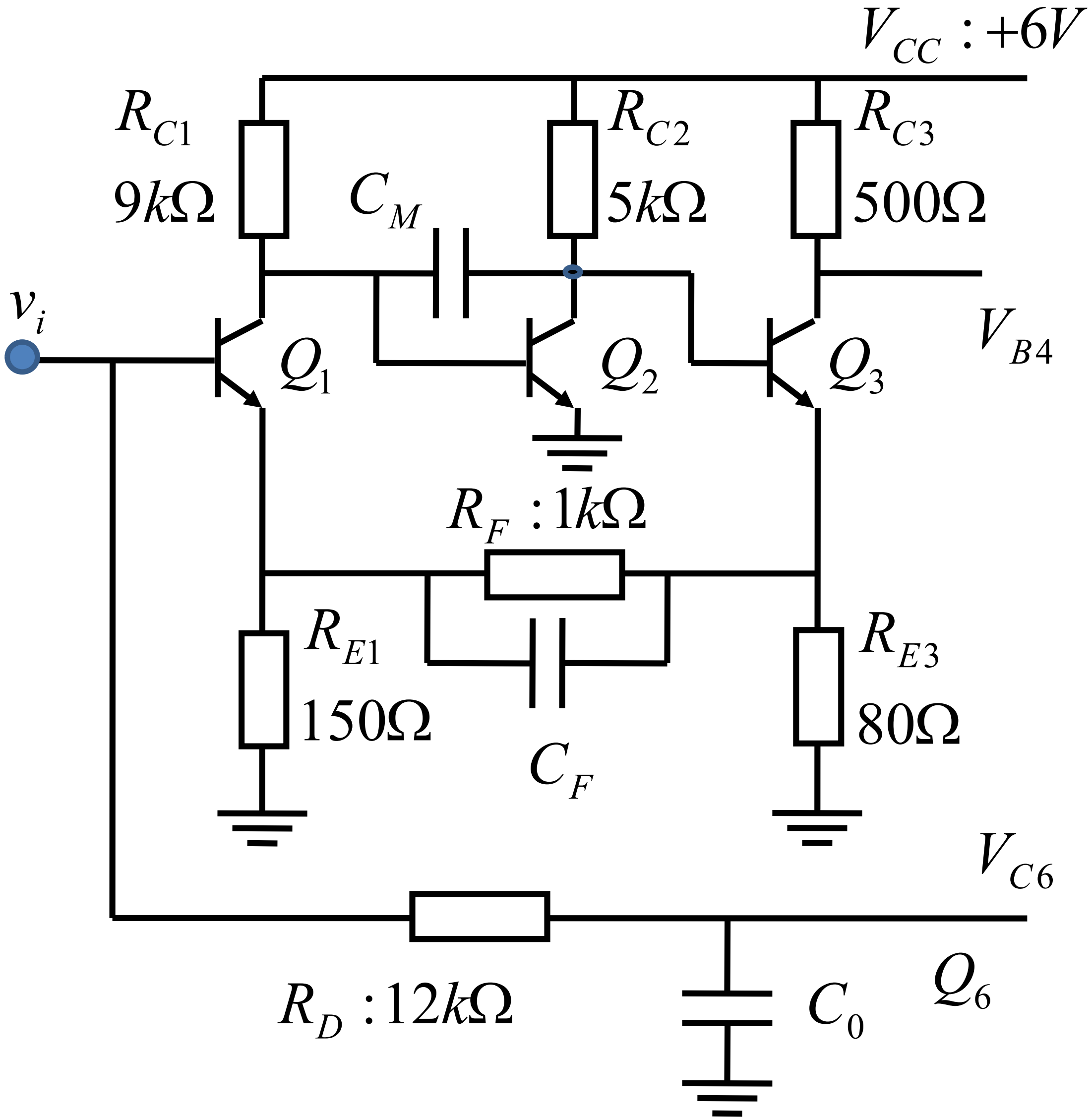


直流负反馈稳定直流工作点



形成直流负反馈通路
同时也是直流偏置电路
该通路对交流不起作用

直流工作点估算



$$V_{BE2} = 0.7V$$

$$V_{C1} = 0.7V$$

$$I_{C1} = \frac{V_{CC} - V_{C1}}{R_{C1}}$$

$$= \frac{6-0.7}{9k} = 0.59mA$$

$$V_{E1} \approx I_E R_{E1} \approx 0.09V$$

$$V_{CE1} \approx 0.6V$$

$$I_{B1} = \frac{I_{C1}}{\beta_{dc1}} \approx \frac{0.59m}{50} = 11.8\mu A$$

$$V_{C6} = I_{B1} R_D + V_{B1}$$

$$\approx 0.14 + 0.7 + 0.09 = 0.93V$$

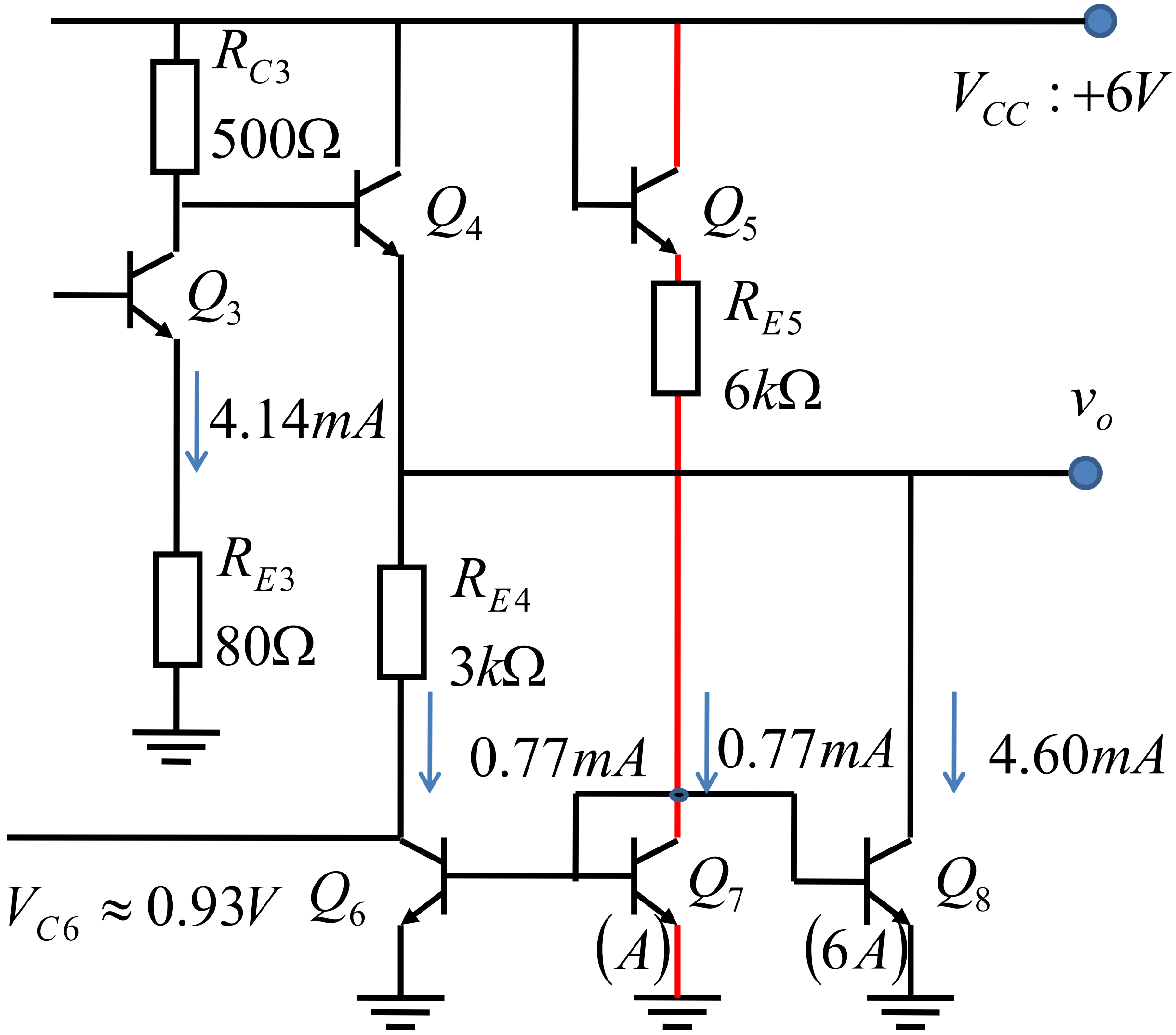
$$V_{E4} = V_{C6} + V_{R_{E4}}$$
$$\approx 0.93 + 2.3 = 3.23V$$

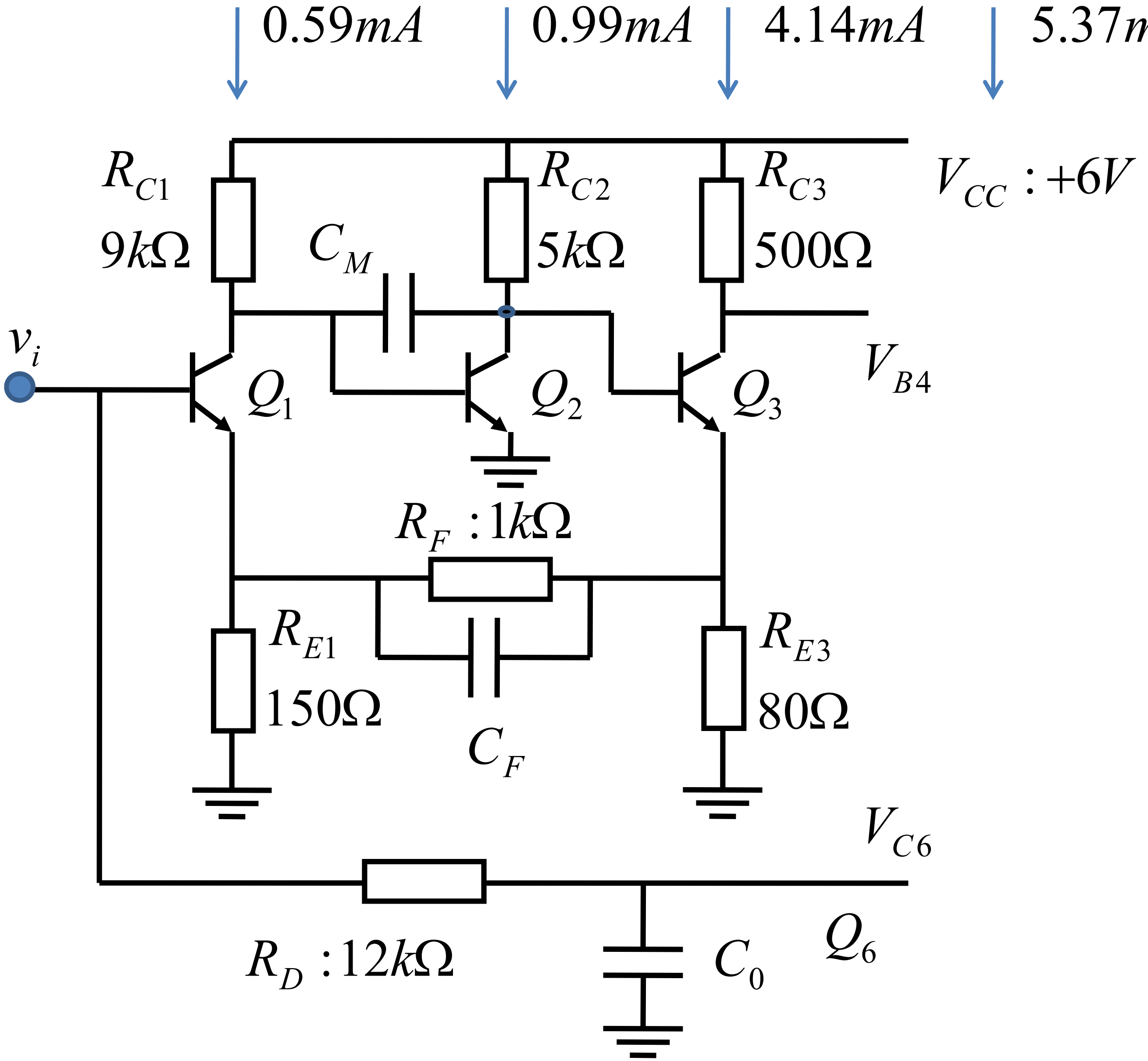
$$V_{B4} = V_{BE4} + V_{E4} \approx 3.93V$$

$$I_{C3} = \frac{V_{CC} - V_{B4}}{R_{C3}}$$
$$\approx \frac{6 - 3.93}{500} = 4.14mA$$

$$V_{E3} = I_{E3} R_{E3}$$
$$\approx 4.14m \times 80 = 0.33V$$

$$V_{B3} = V_{BE3} + V_{E3}$$
$$\approx 0.7 + 0.33 = 1.03V$$





$$V_{B3} \approx 1.03V$$

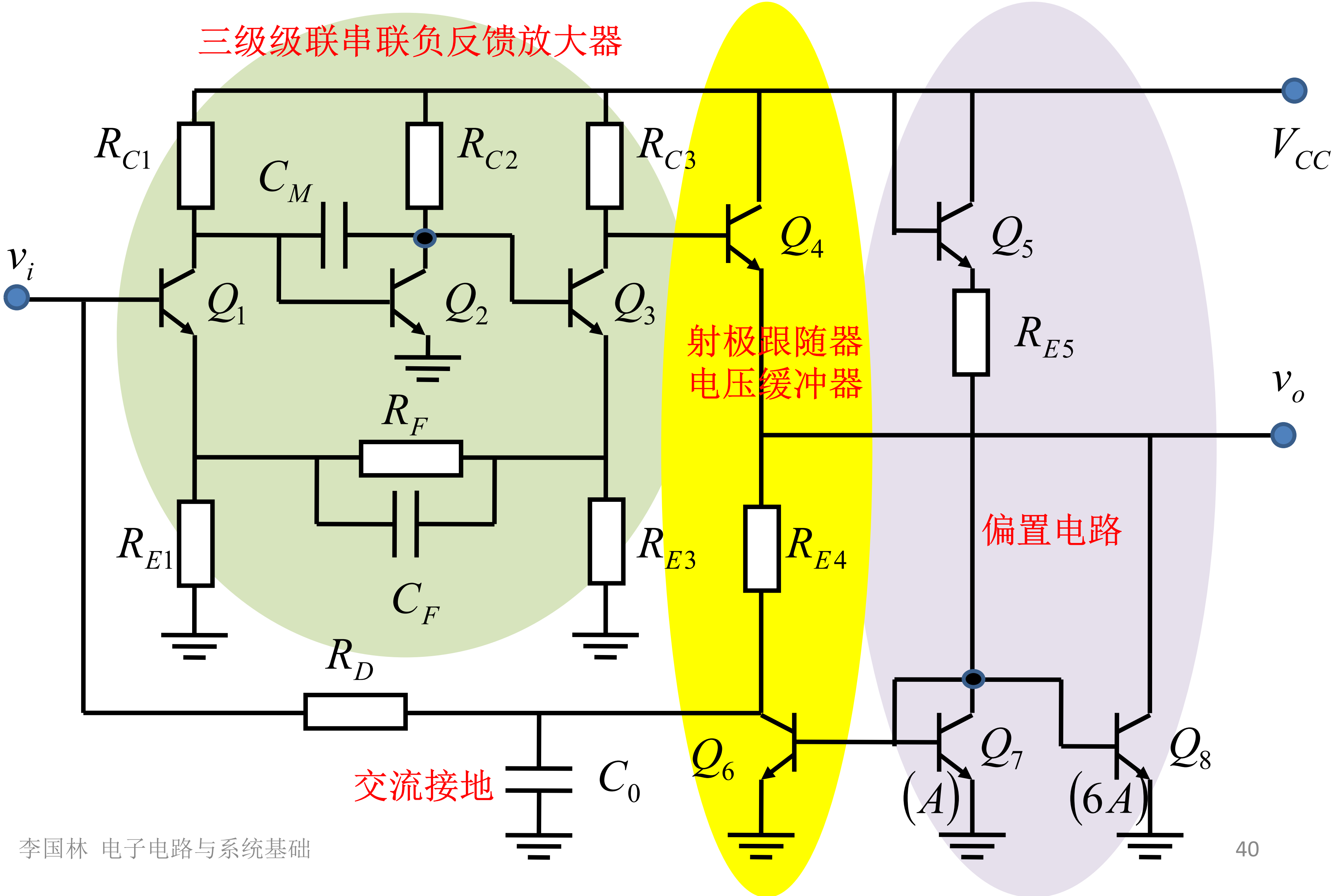
$$I_{C2} = \frac{V_{CC} - V_{B3}}{R_{C2}} \approx \frac{6-1.03}{5k} = 0.99mA$$

$$I_{\Sigma} \approx 11.86mA$$

$$P_{DC} = I_{\Sigma} V_{CC} \approx 71mW$$

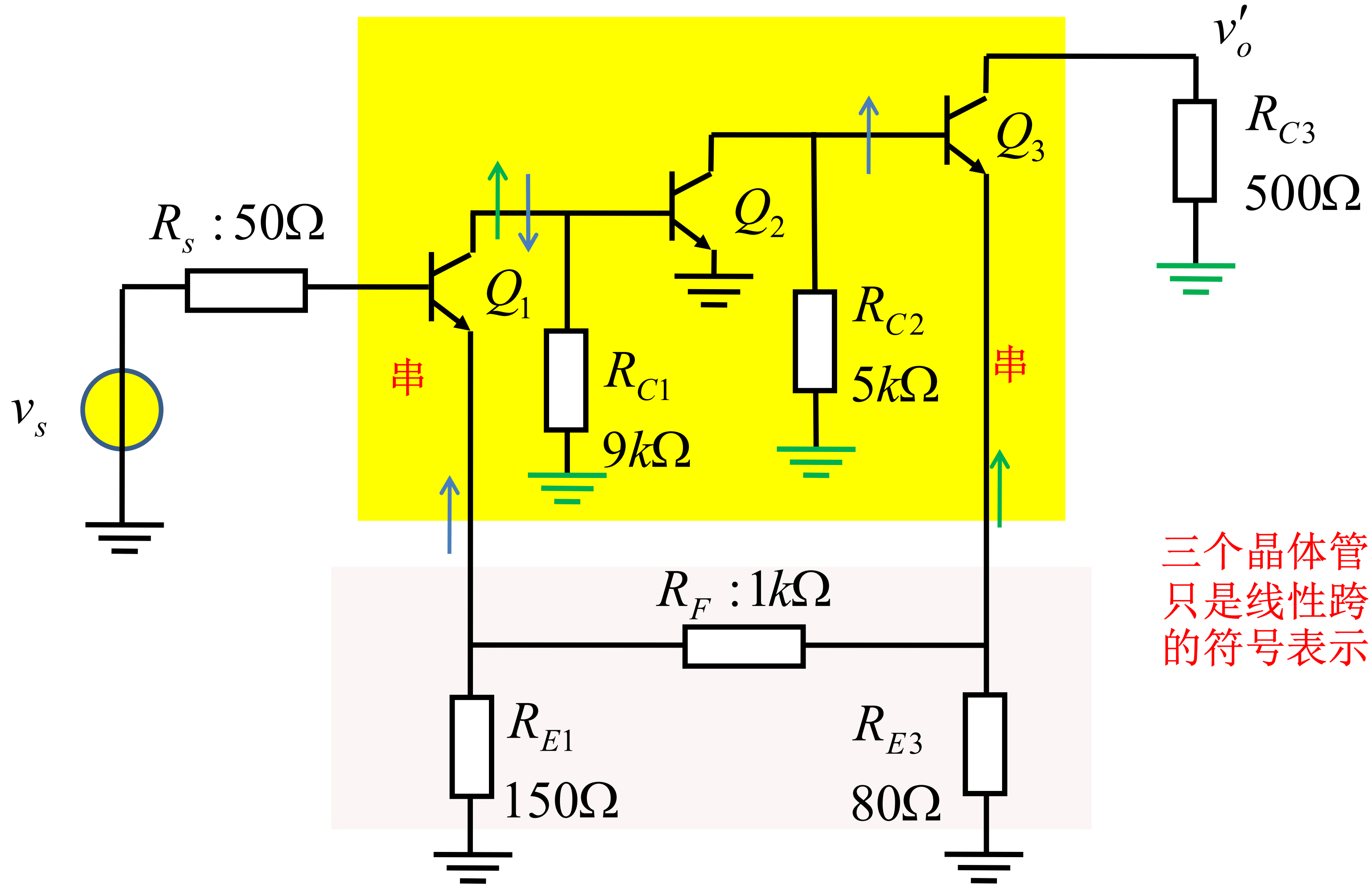
直流分析确认每个晶体管都是有源导区通

交流小信号放大



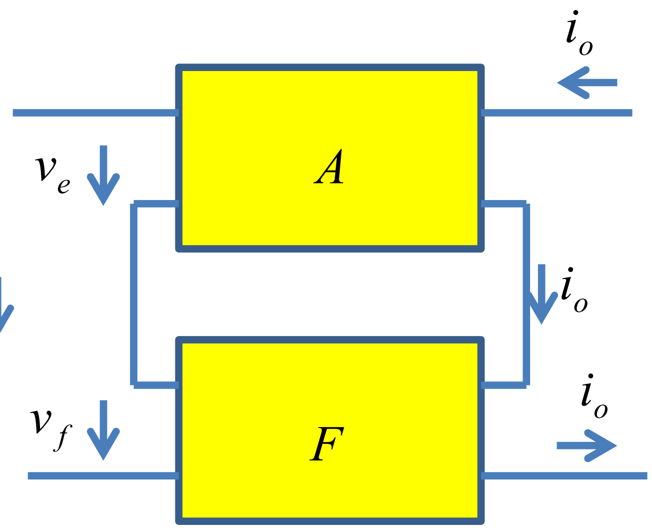
三级级联串联负反馈放大器
R_{C1}
C_M
R_{C2}
R_{C3}
V_{CC}
Q_4
Q_5
v_i
Q_1
Q_2
Q_3
射极跟随器
电压缓冲器
R_{E5}
v_o
R_F
偏置电路
R_{E1}
R_{E3}
R_{E4}
C_F
R_D
Q_6
Q_7
Q_8
交流接地
C_0
(A)
(6A)

三级级联串联负反馈



三个晶体管符号
只是线性跨导器
的符号表示

串串连接 z 相加



$$\mathbf{z}_{AF} = \mathbf{z}_A + \mathbf{z}_F = \begin{bmatrix} z_{A,11} & 0 \\ z_{A,21} & z_{A,22} \end{bmatrix} + \begin{bmatrix} z_{F,11} & z_{F,12} \\ z_{F,21} & z_{F,22} \end{bmatrix}$$

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

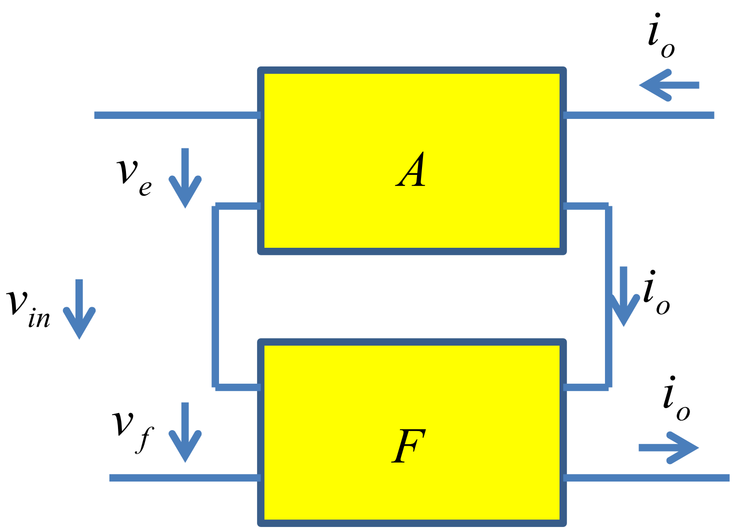
$$= \begin{bmatrix} z_{A,11} + z_{F,11} & 0 \\ z_{A,21} + z_{F,21} & z_{A,22} + z_{F,22} \end{bmatrix} + \begin{bmatrix} 0 & z_{F,12} \\ 0 & 0 \end{bmatrix}$$

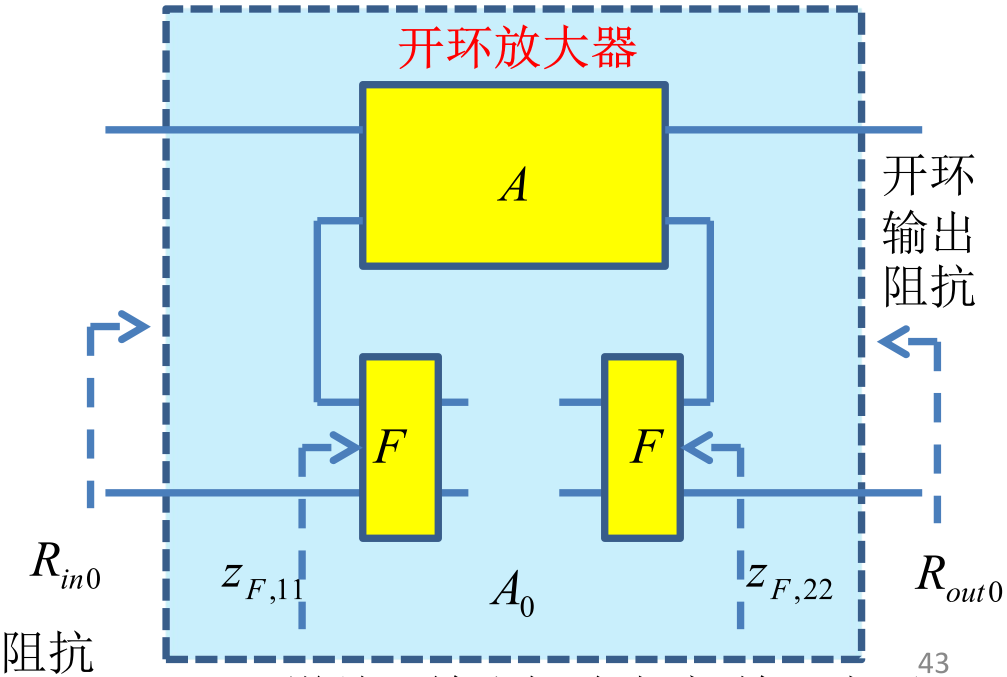
$$\approx \begin{bmatrix} z_{A,11} + z_{F,11} & 0 \\ z_{A,21} & z_{A,22} + z_{F,22} \end{bmatrix} + \begin{bmatrix} 0 & z_{F,12} \\ 0 & 0 \end{bmatrix} = \mathbf{z}_{A,openloop} + \mathbf{z}_{F,ideal}$$

开环放大器

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

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

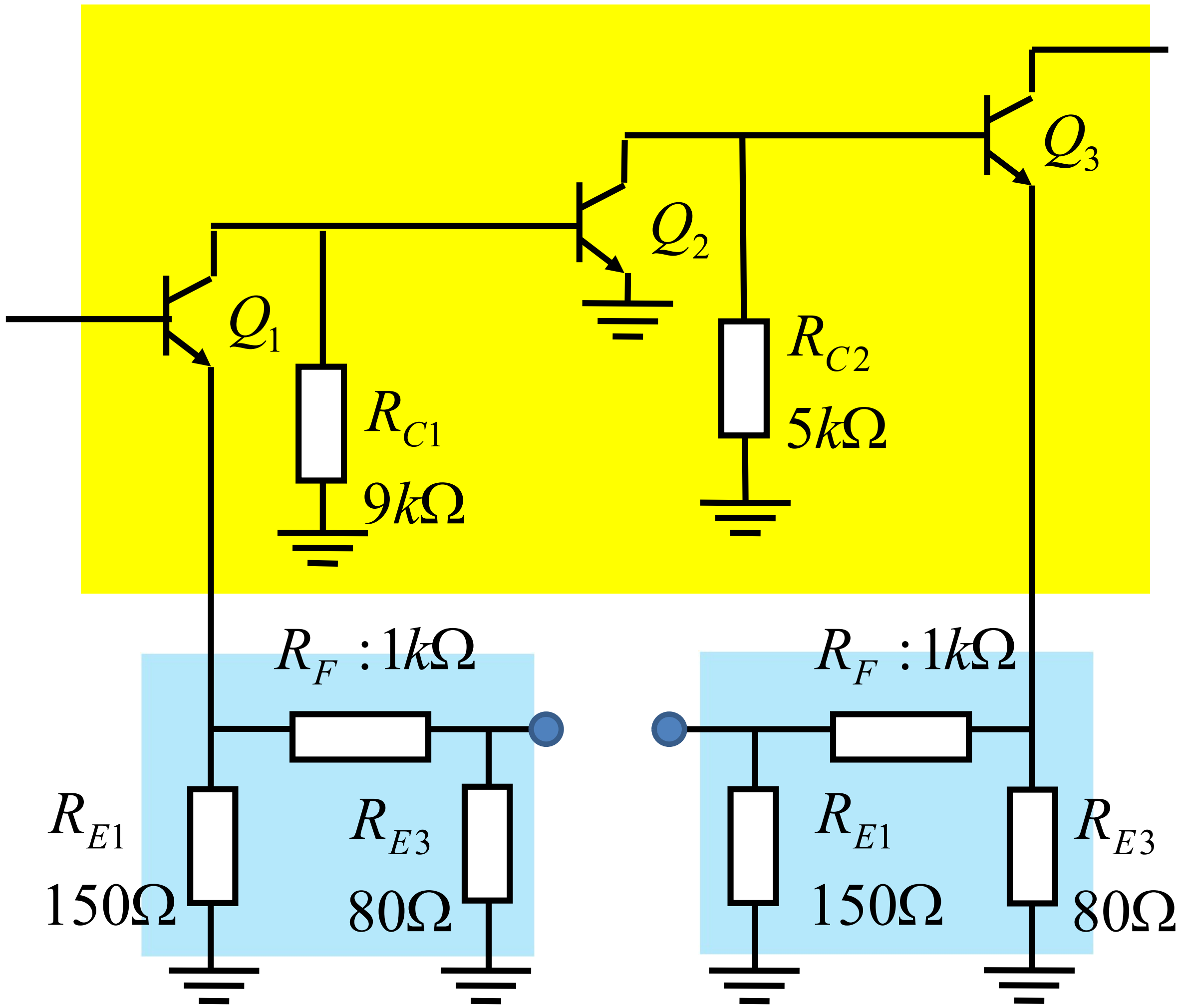


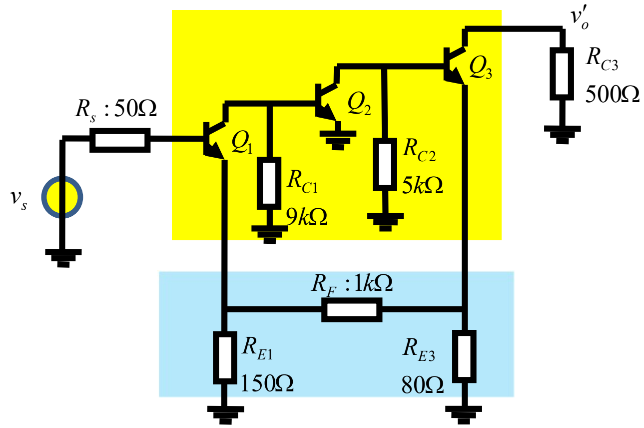


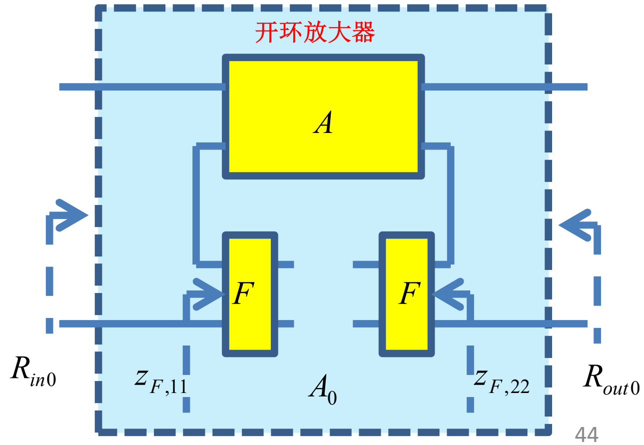
开环输入阻抗

开环增益：输出短路电流/输入电压

开环放大器





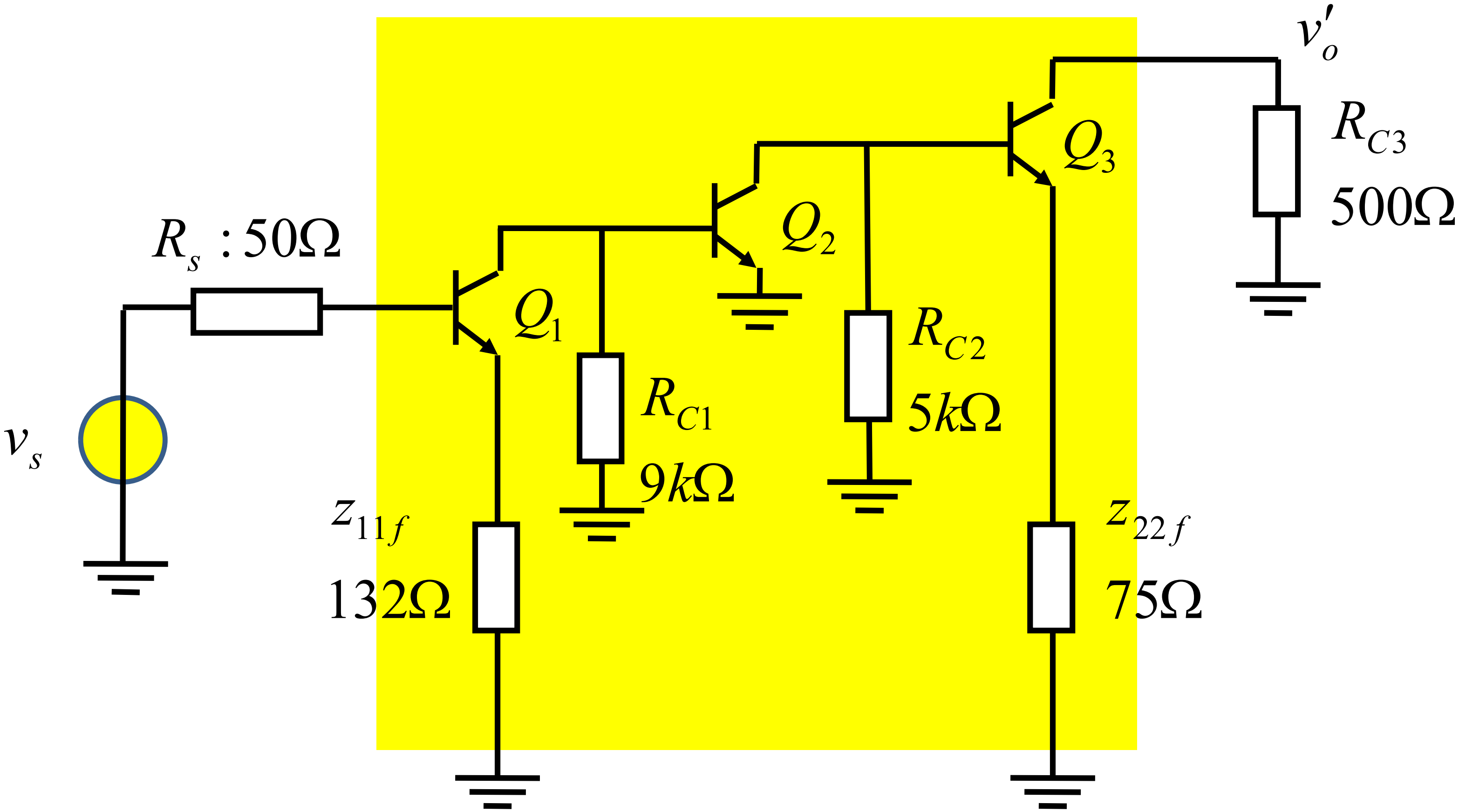


开环增益：输出短路电流/输入电压

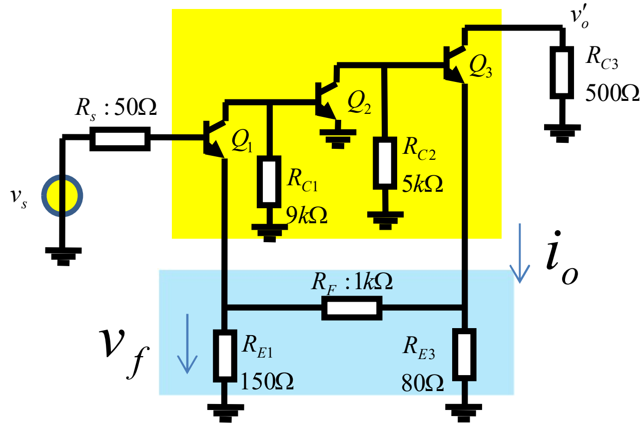
$$150\Omega \,||\, \left(80\Omega + 1k\Omega\right) = 132\Omega$$

$$80\Omega \,||\, \left(150\Omega + 1k\Omega\right) = 75\Omega$$

开环放大器



理想反馈网络



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

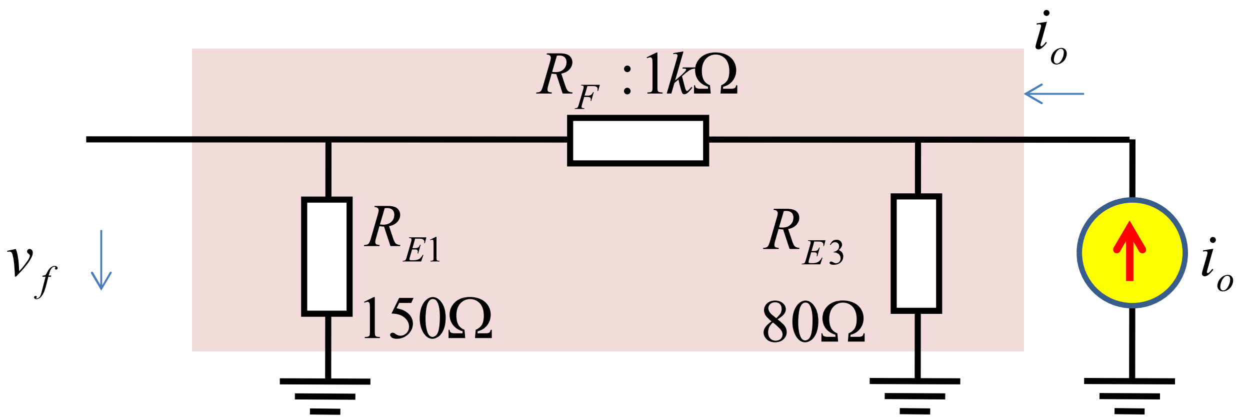
$$= \mathbf{z}_{A,openloop} + \mathbf{z}_{F,ideal}$$

$$\mathbf{z}_{F,ideal} = \begin{bmatrix} 0 & z_{F,12} \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & F \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & R_F \\ 0 & 0 \end{bmatrix}$$

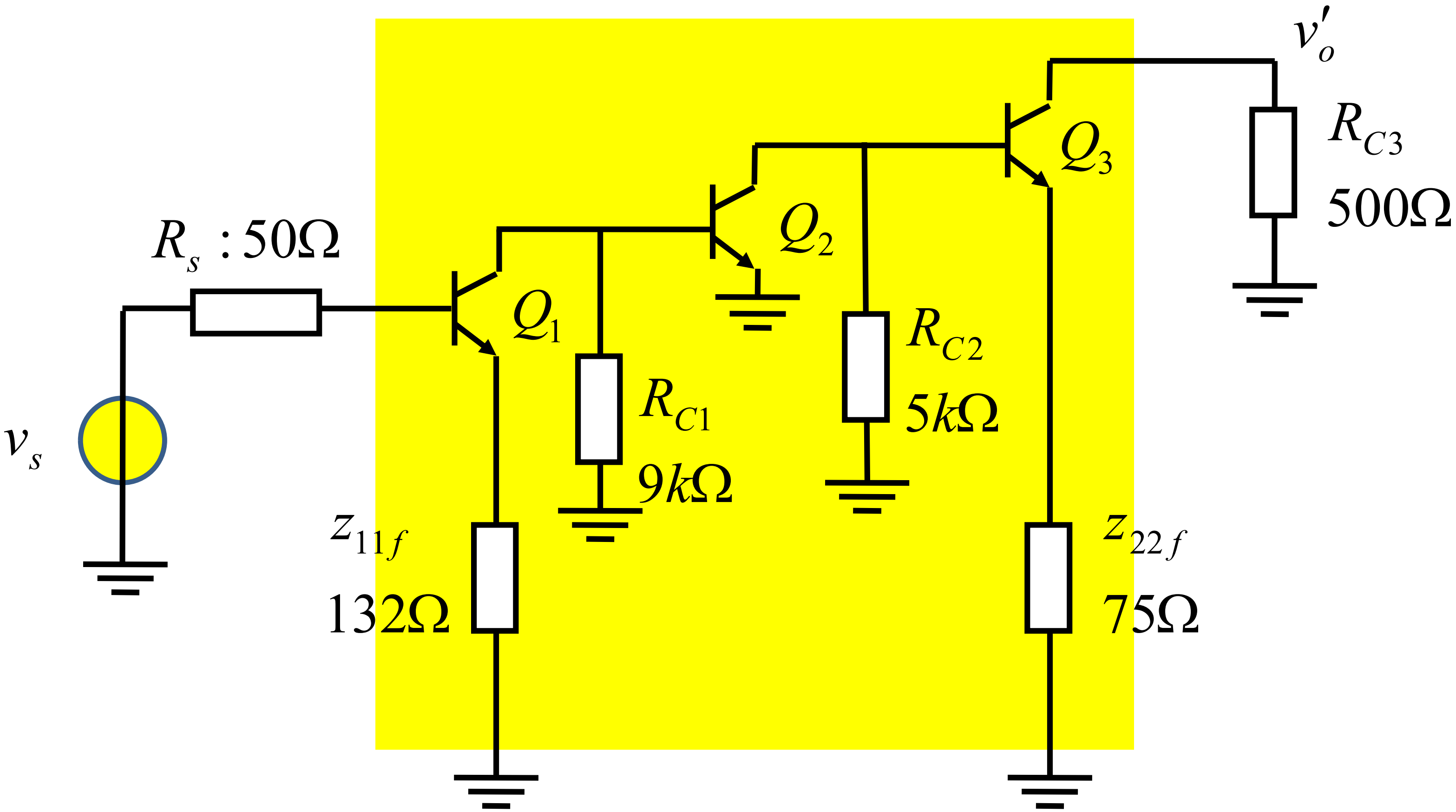
$$F = z_{F,12} = R_F = \frac{v_f}{i_o}$$

$$= \frac{R_{E1}}{R_F + R_{E1}}\left[R_{E3} \parallel \left(R_F + R_{E1}\right)\right]$$

$$= \frac{R_{E1}R_{E3}}{R_{E1}+R_F+R_{E3}} = 9.76\Omega$$

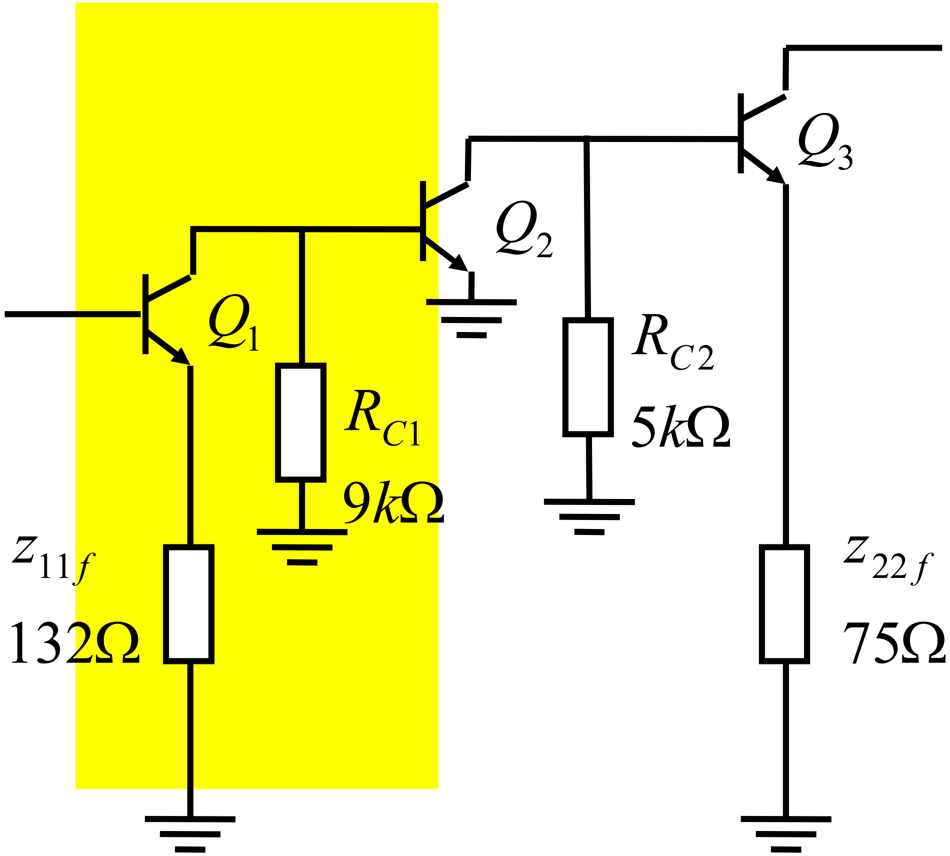


开环放大网络分析



多级级联，高增益，以确保深度负反馈

第一级



假设β=50，V_A=50V

$$g_{m1}=\frac{I_{C1}}{v_T}\approx\frac{0.59m}{26m}=23mS$$

$$G_{m1}\approx\frac{g_{m1}}{1+g_{m1}z_{11f}}$$

$$=\frac{23m}{1+23m\times132}=\frac{23m}{4}=5.7mS$$

$$r_{in1}=\left(1+g_{m1}z_{11f}\right)r_{be1}$$

$$\approx\left(1+23m\times132\right)\times50\times\frac{1}{23m}$$

$$=8.79k\Omega$$

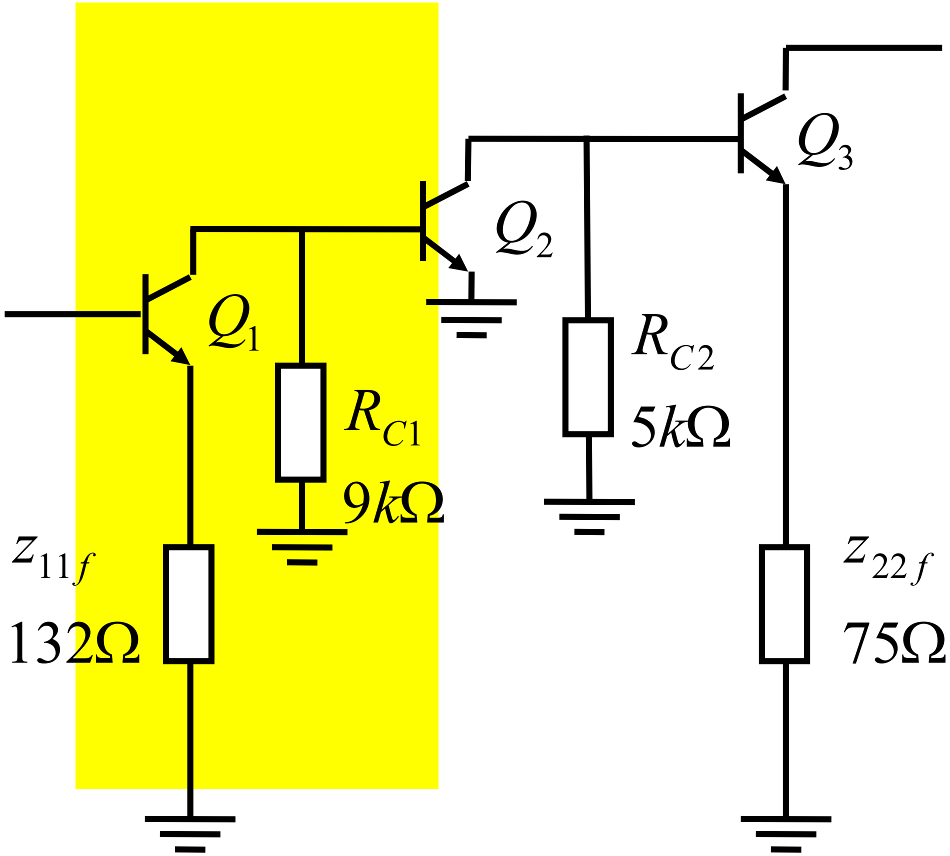
$$r_{out1}=\left(1+g_{m1}z_{11f}\right)r_{ce1}$$

$$\approx\left(1+23m\times132\right)\times\frac{50}{0.59m}$$

$$=338k\Omega$$

第一级

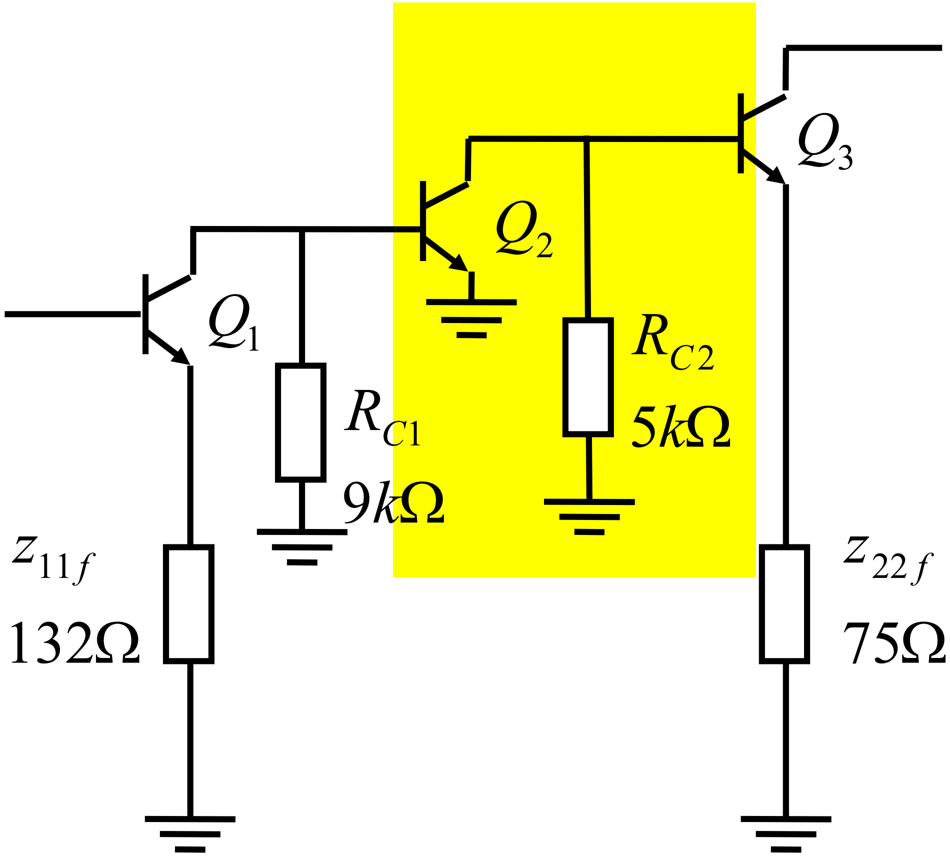
$$r_{be2} = \beta \frac{v_T}{I_{C2}} = 50 \times \frac{26m}{0.99m} = 1.31k\Omega$$



$$R'_{L1} = r_{out1} \parallel R_{C1} \parallel r_{be2}$$
$$= 338k \parallel 9k \parallel 1.31k = 1.14k\Omega$$

$$A_{v1} = -G_{m1} R'_{L1}$$
$$= -5.7m \times 1.14k$$
$$= -6.50$$

第二级



$$g_{m2}=\frac{I_{C2}}{v_T}\approx\frac{0.99m}{26m}=38.1mS$$

$$g_{m3}=\frac{I_{C3}}{v_T}\approx\frac{4.14m}{26m}=159mS$$

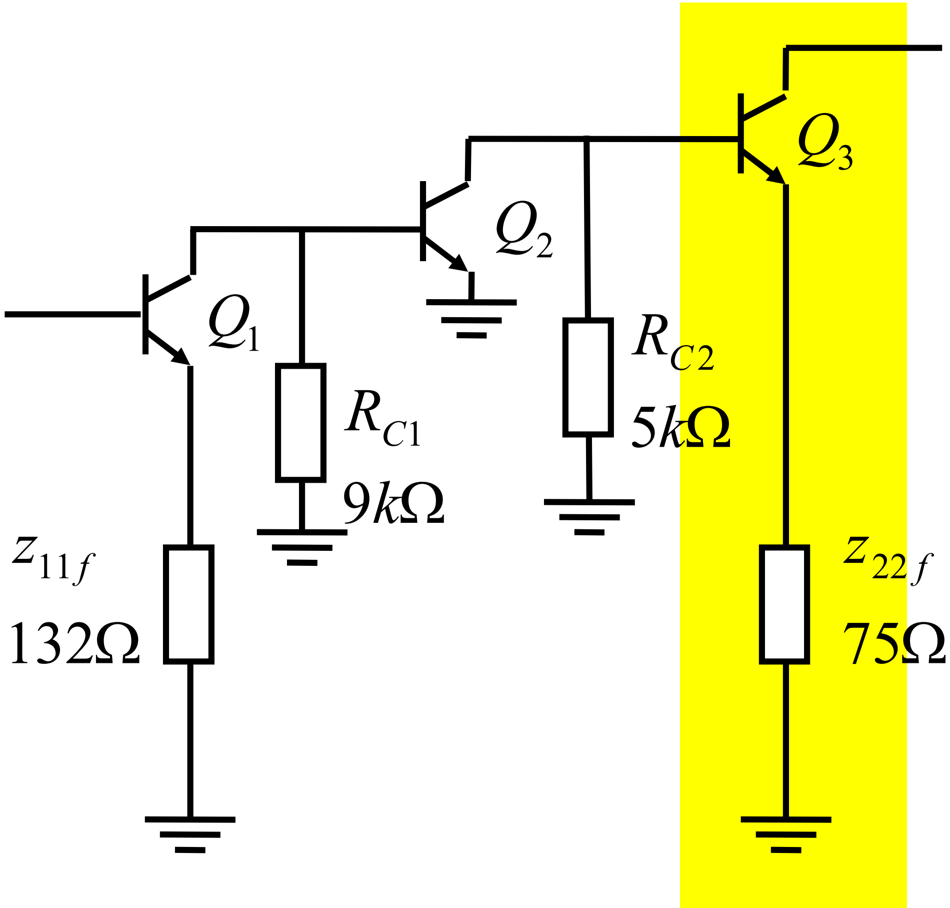
$$r_{in3}=\left(1+g_{m3}z_{22f}\right)r_{be3}$$
$$=\left(1+159m\times75\right)\times50\times\frac{26m}{4.14m}$$
$$=4.05k\Omega$$

$$R'_{L2}=r_{ce2}\,||\,R_{C2}\,||\,r_{in3}$$
$$=\frac{50}{0.99m}\,||\,5k\,||\,4.05k$$
$$=2.14k\Omega$$

$$A_{v2}=-g_{m2}R'_{L2}$$
$$=-38.1m\times2.14k=-81.6$$

第三级

$$g_{m3}=\frac{I_{C3}}{v_T}\approx\frac{4.14m}{26m}=159mS$$



$$G_{m3}=\frac{g_{m3}}{1+g_{m3}z_{22f}}$$

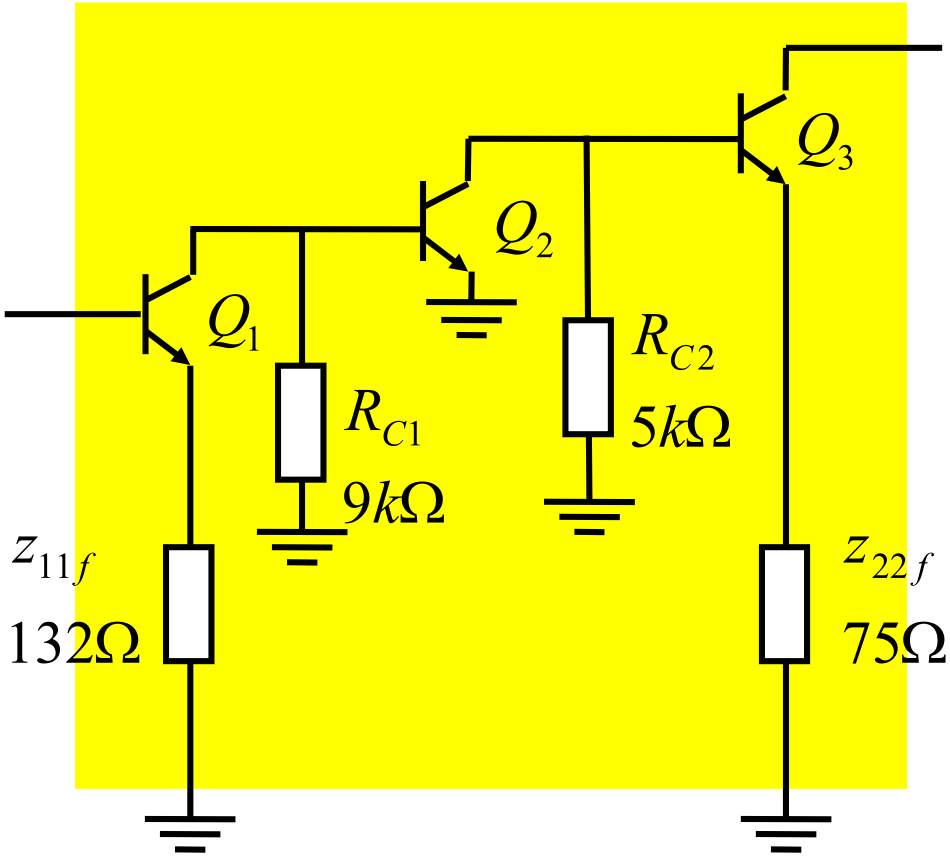
$$=\frac{159m}{1+159m\times 75}=12.3mS$$

$$r_{out3}=\left(1+g_{m3}z_{22f}\right)r_{ce3}$$

$$=\left(1+159m\times 75\right)\times\frac{50}{4.14m}$$

$$=156k\Omega$$

三级级联：开环跨导放大器



$$r_{inA} = (1 + g_{m1} z_{11f}) r_{be1} = 8.79k\Omega$$

$$r_{outA} = (1 + g_{m3} z_{22f}) r_{ce3} = 156k\Omega$$

$$G_{m0} = A_{v1} A_{v2} G_{m3}$$
$$= 6.50 \times 81.6 \times 12.3m$$
$$= 6.54S$$

$$T = G_{m0} R_F = 6.54S \times 9.76\Omega = 63.8 >> 1$$

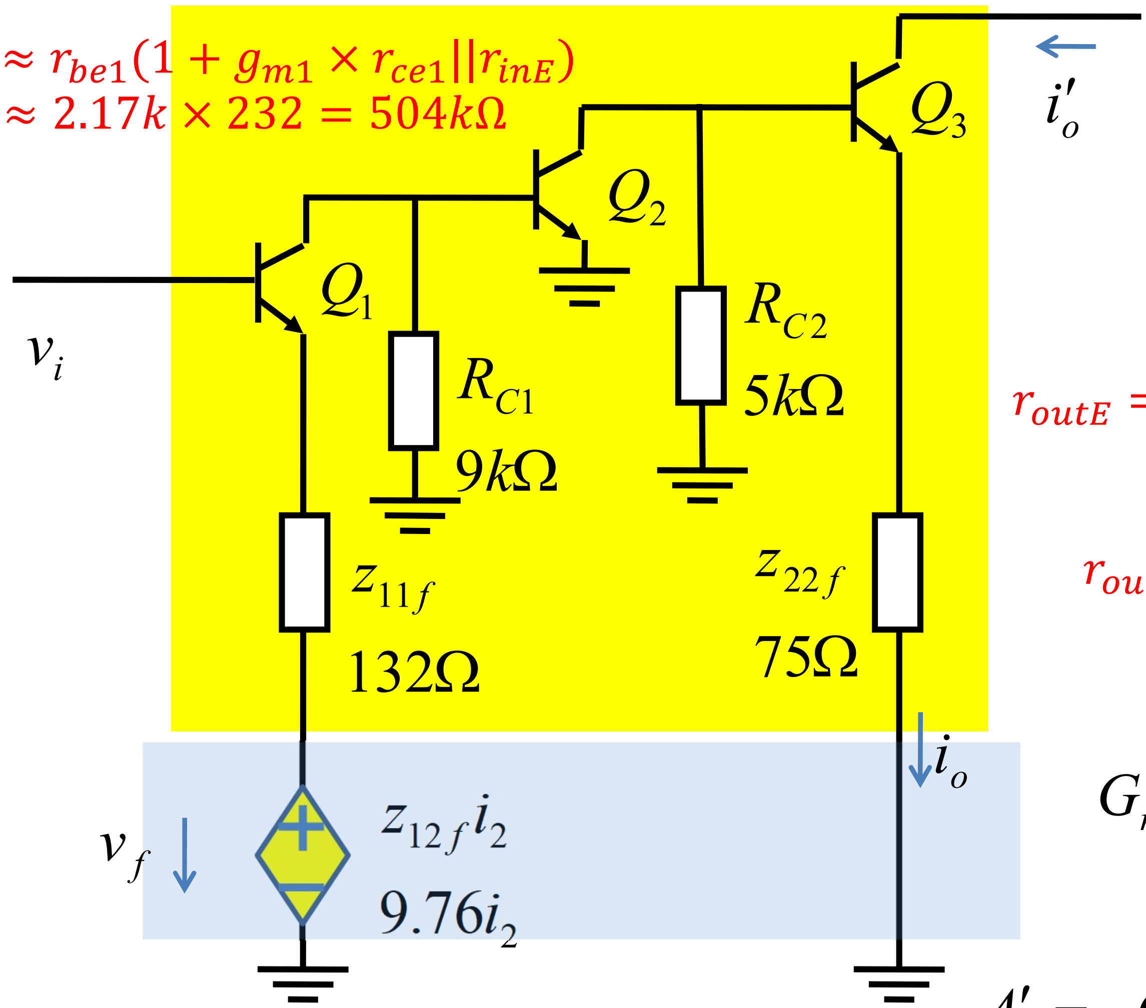
负反馈跨导放大器

$$T = G_{m0}R_F = 6.54\times 9.76 = 63.8$$

$$r_{inE} = (1+T)\left(z_{11} + \frac{1}{g_{m1}}\right) = 11.4k\Omega$$

$$r_{in} = (1+T)r_{inA}$$
$$= 64.8\times 8.79k\Omega = 570k\Omega$$

$$r_{in} \approx r_{be1}(1 + g_{m1}\times r_{ce1}||r_{inE})$$
$$\approx 2.17k \times 232 = 504k\Omega$$



$$r_{out} = (1+T)r_{outA}$$
$$= 64.8\times 156k\Omega = 10M\Omega$$ ✗

$$r_{outE} = (1+T)\left(z_{22f} + \frac{1}{g_{m3}}\right) = 5.3k\Omega$$

$$r_{out} \approx r_{ce3}(1 + g_{m3}\times r_{be3}||r_{outE})$$
$$\approx 12k \times 47 = 565k\Omega$$

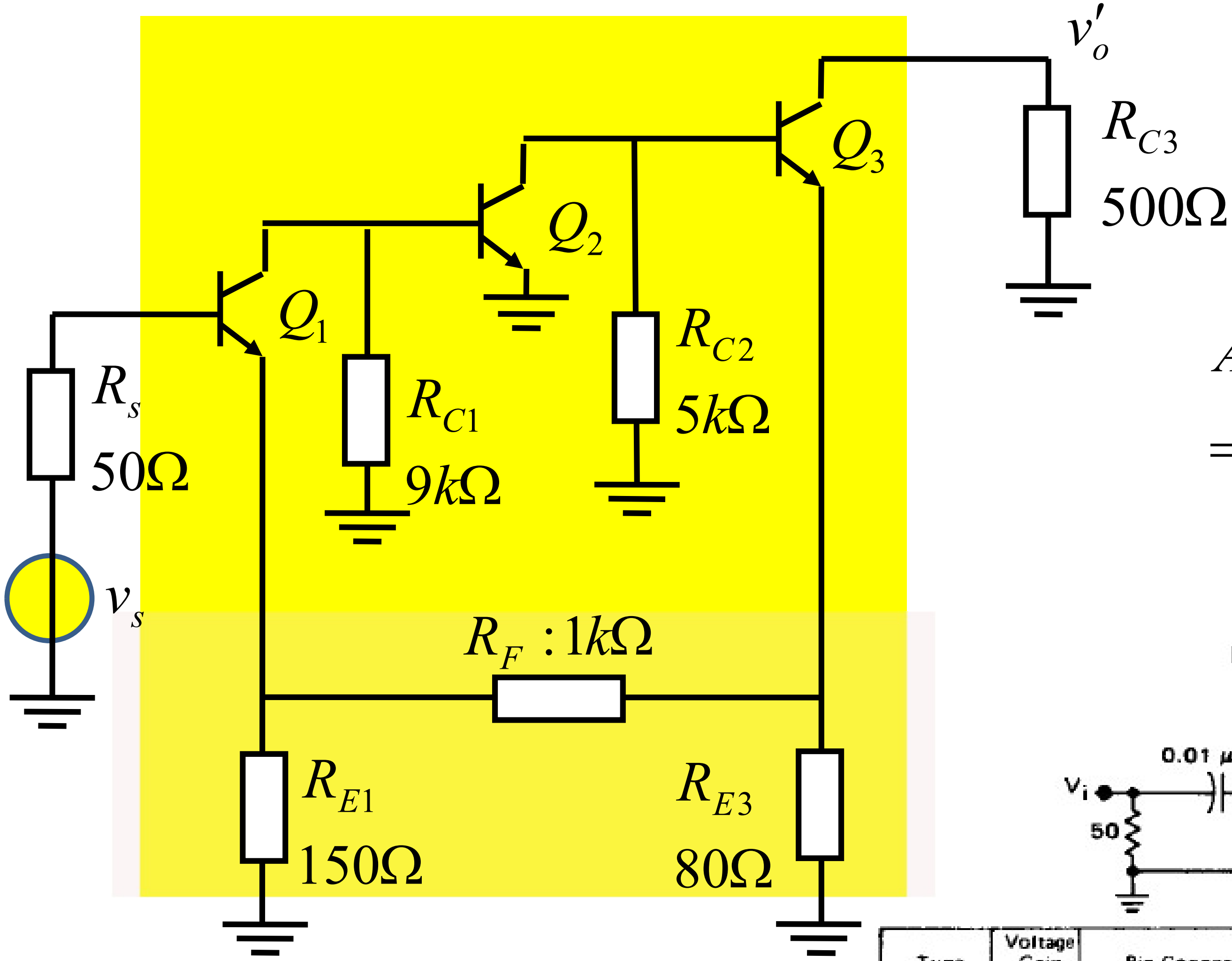
$$G_{mf} = \frac{G_{m0}}{1+T} = \frac{6.54}{64.8} = 101mS$$

$$A'_v = -G_{mf}R_{C3} = 101m\times 500 = -50$$

电压放大倍数

深度负反馈

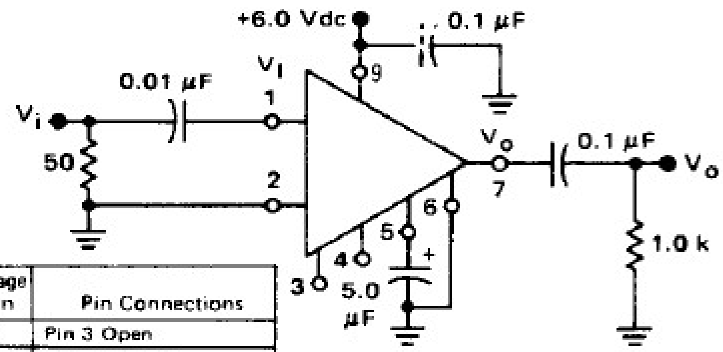
$$G_{mf} \approx \frac{1}{R_F} = \frac{1}{9.76\Omega} = 102mS$$



$$A'_v = -G_{mf} R'_{L3}$$

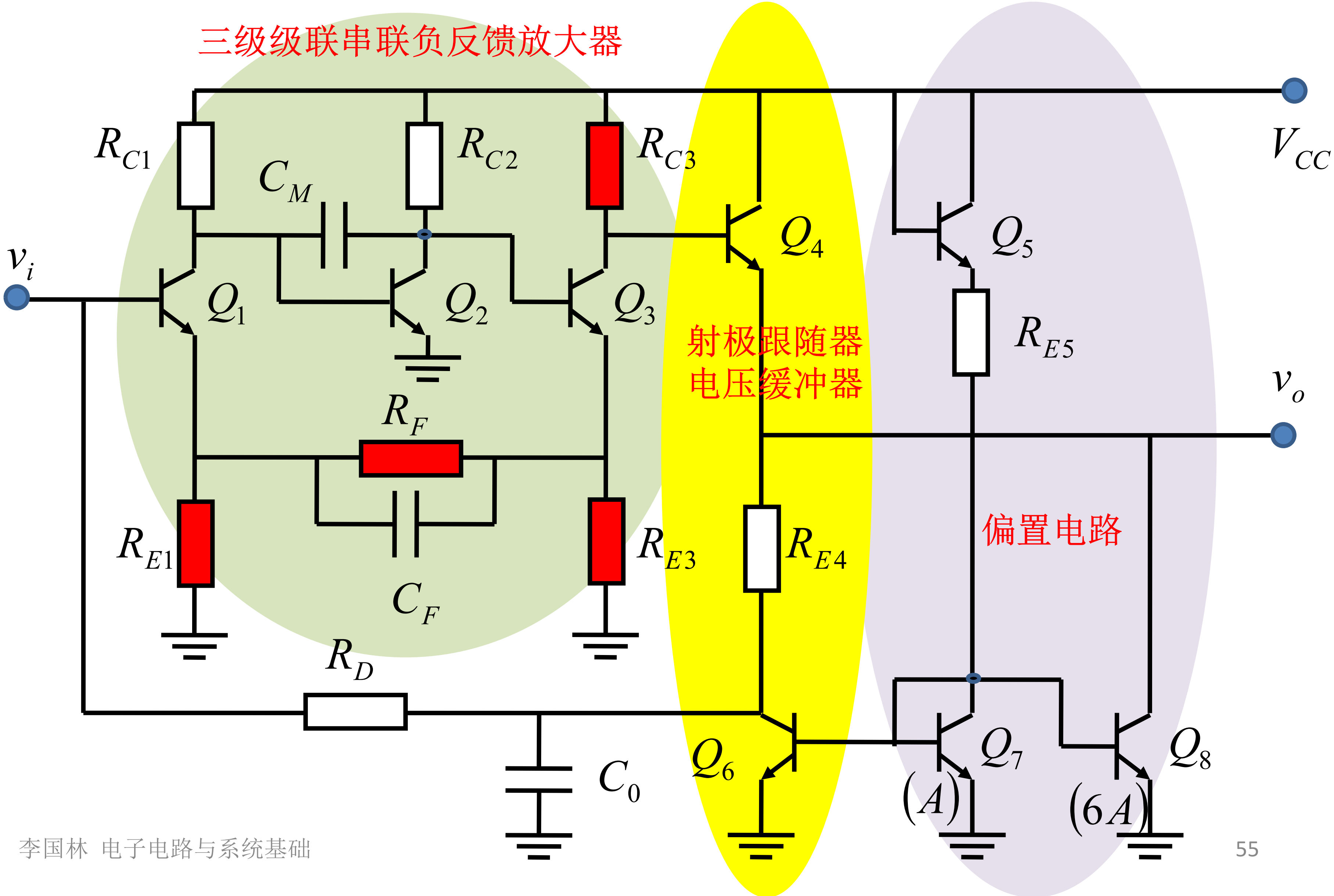
$$= -102m \times 500 = -51$$

FIGURE 3 – TEST CIRCUIT



Type	Voltage Gain	Pin Connections
MC1552	50	Pin 3 Open
	100	Ground Pin 3

负反馈网络的存在，增益由电阻决定



负反馈网络的存在，增益由电阻决定

$$R_F = \frac{R_{E1}R_{E3}}{R_{E1} + R_F + R_{E3}}$$

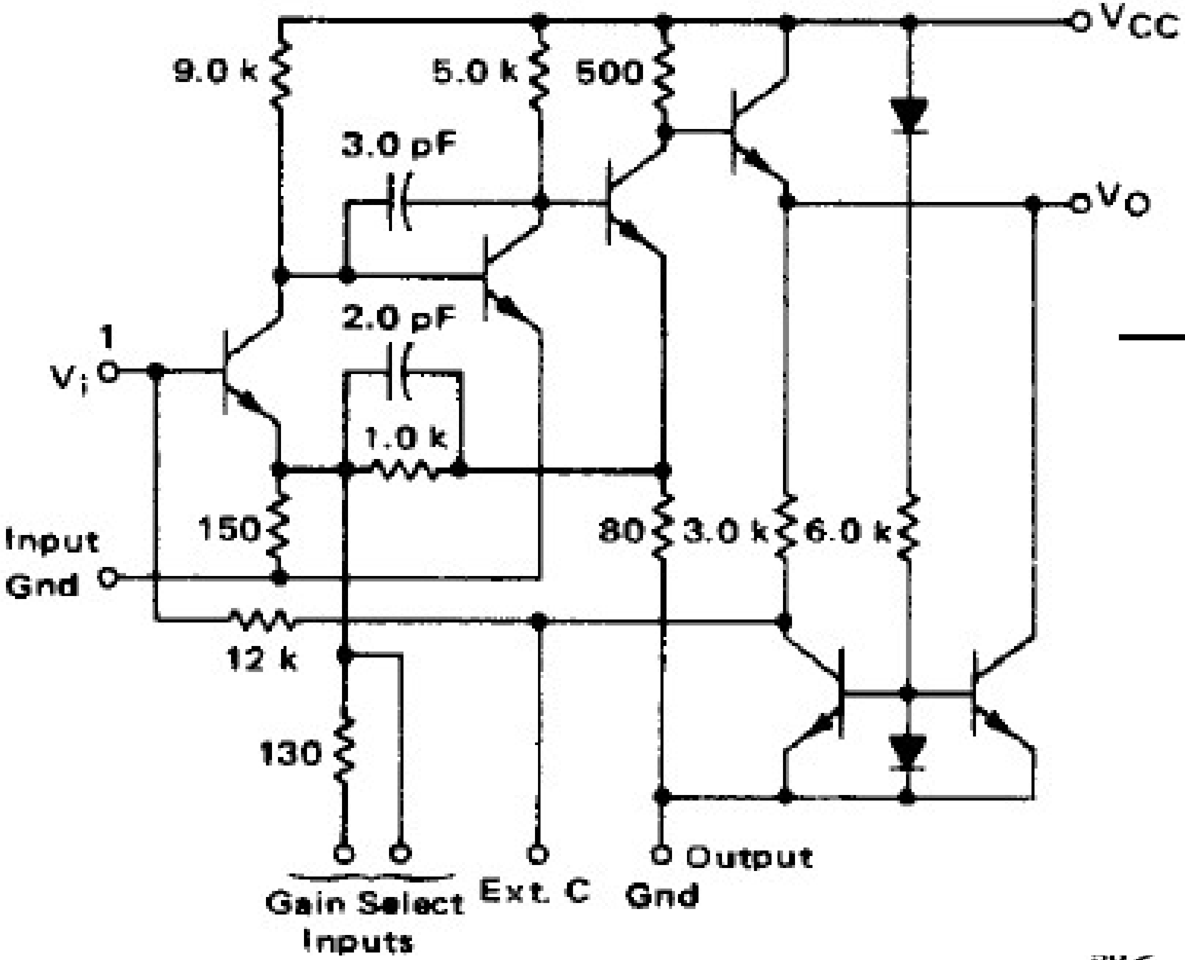
$$G_{mf} \approx \frac{1}{R_F} = \frac{R_{E1} + R_F + R_{E3}}{R_{E1}R_{E3}}$$

$$A_v' \approx -G_{mf}R_{L3}' = -\frac{R_{E1} + R_F + R_{E3}}{R_{E1}R_{E3}}R_{C3}$$

增益几乎完全由电阻网络决定
晶体管网络仅提供深度负反馈需要的高增益

晶体管网络不稳定，增益不确定
但电阻网络稳定，闭环后增益由电阻网络决定，增益稳定

管脚3接地



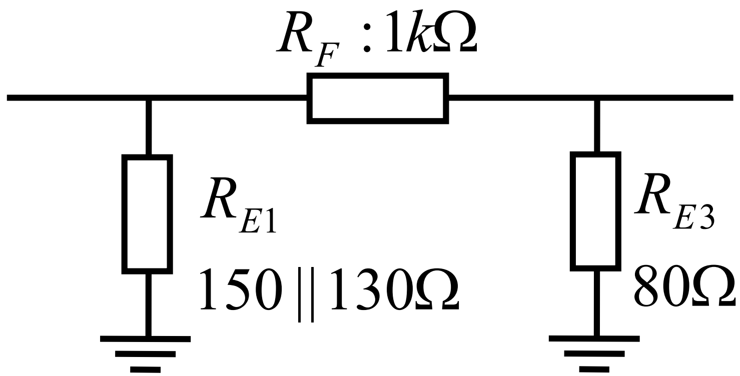
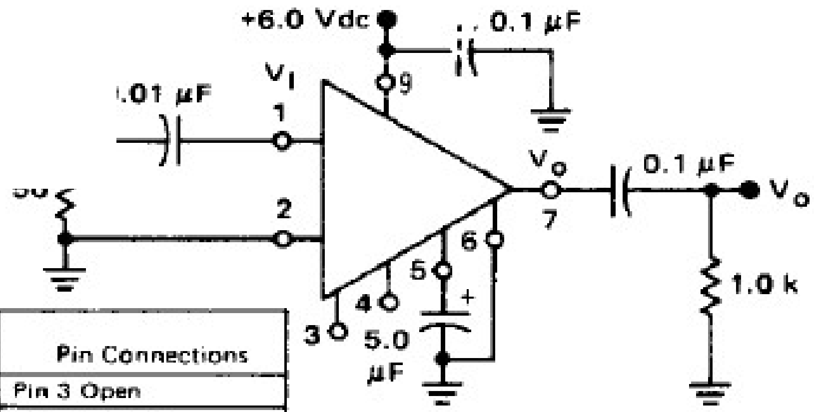


FIGURE 3 – TEST CIRCUIT



Type	Voltage Gain	Pin Connections
MC1552	50	Pin 3 Open
	100	Ground Pin 3

同学自行确认增益为**100**！

如果希望增益为**80**？如何处理？

级联放大器有时无需分析开环放大器

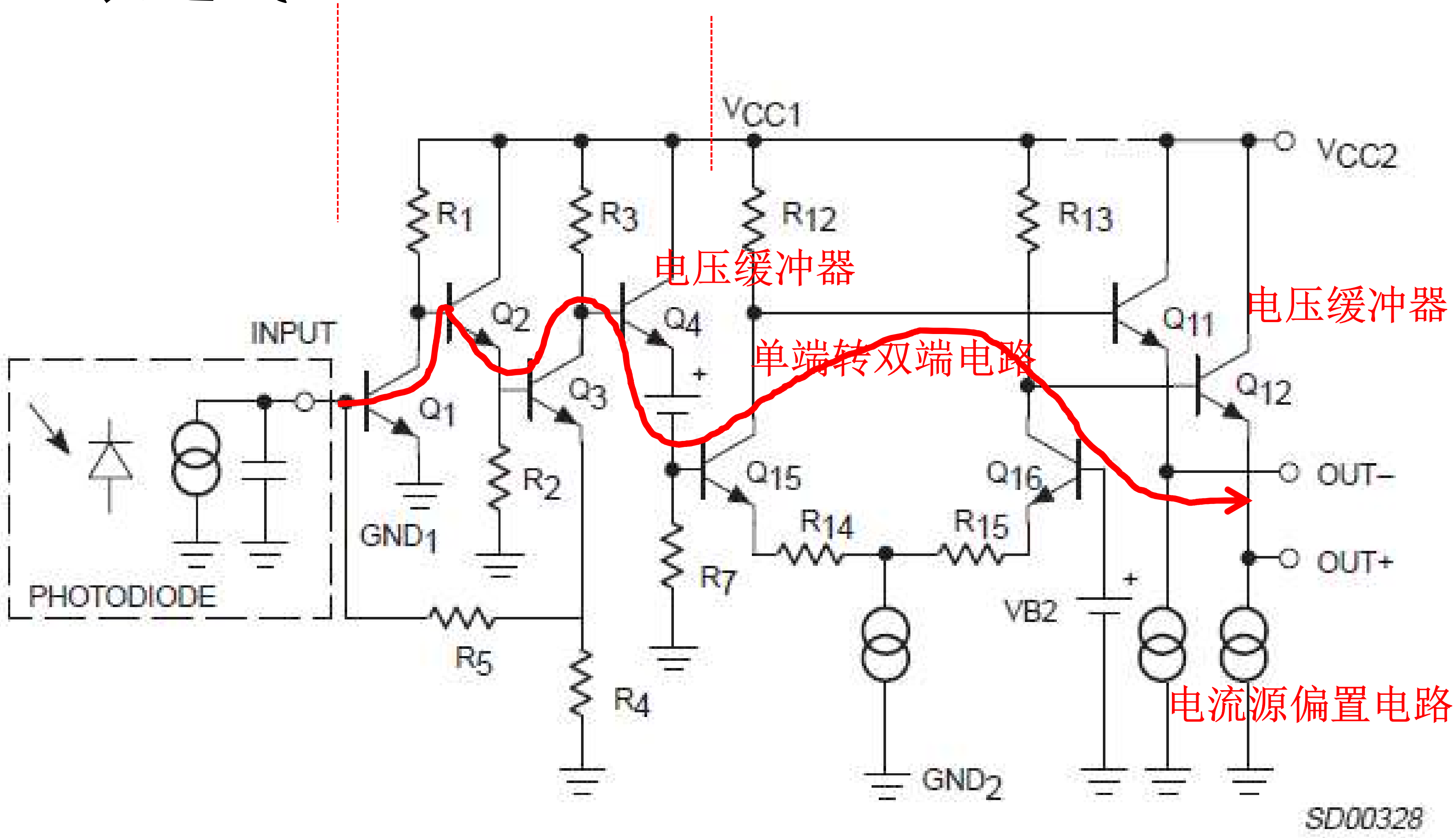
- 级联，高增益，深度负反馈
  - 输入电阻、输出电阻变得接近理想受控源
    - 由于输入电阻和输出电阻接近理想短路或开路，和信源内阻、负载比，其影响可以忽略不计，因而经常性地不予关注

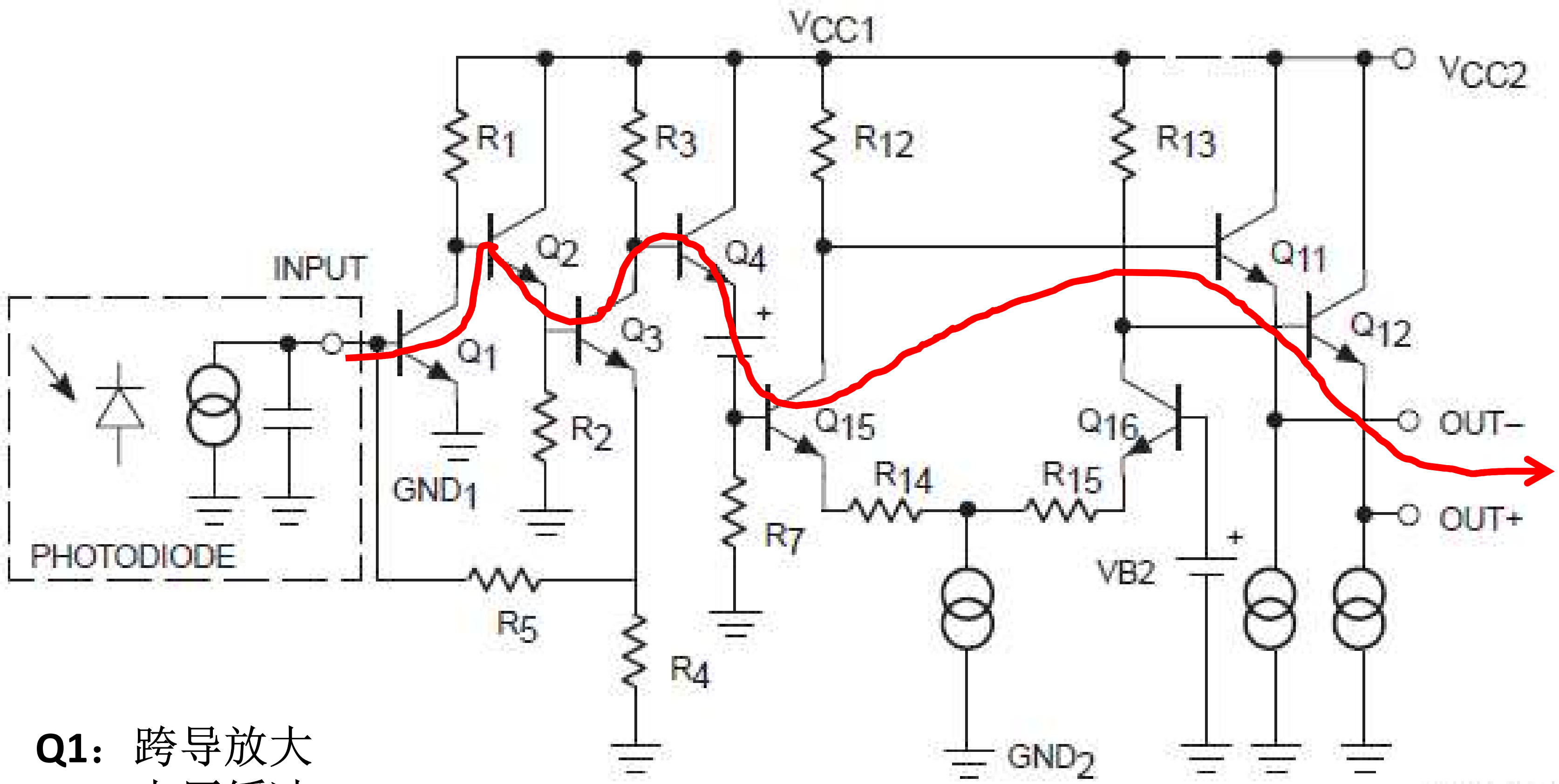
- 我们只对增益感兴趣
  - 只需计算反馈系数即可
    - 串串负反馈
      - 反馈网络输入端加电流源激励，反馈网络输出端测开路电压，获得跨阻反馈系数（检测输出电流，形成反馈电压）
    - 并并负反馈
      - 反馈网络输入端家电压源激励，反馈网络输出端测短路电流，获得跨导反馈系数（检测输出电压，形成反馈电流）
    - 串并负反馈
      - 反馈网络输入端加电压源激励，反馈网络输出端测开路电压，获得电压反馈系数（检测输出电压，形成反馈电压）
    - 并串负反馈
      - 反馈网络输入端加电流源激励，反馈网络输出端测短路电流，获得电流反馈系数（检测输出电流，形成反馈电流）

前述例子，只分析反馈网络即可获得增益

  - 反馈系数的倒数就是闭环增益

- **PHILIPS的SA5211自称是Transimpedance Amplifier，其内部电路如图所示，求输入到Q_4输出的跨阻增益表达式**





Q1： 跨导放大
Q2： 电压缓冲
Q3： 跨导放大
Q4： 电压缓冲
…

并串负反馈：形成流控流源

$$F_i = -\frac{G_5}{G_4 + G_5} = -\frac{R_4}{R_4 + R_5} \qquad A_{if} = \frac{1}{F_i} = -\left(1 + \frac{R_5}{R_4}\right)$$

$$R_m = \frac{v_{o3}}{i_{in}} = -\frac{i_3 R_3}{i_{in}} = -\frac{1}{F_i} R_3 = \left(1 + \frac{R_5}{R_4}\right) R_3$$

$$R_{m\Sigma} = \left(1 + \frac{R_5}{R_4}\right) R_3 \frac{R_{12}}{R_{14}}$$

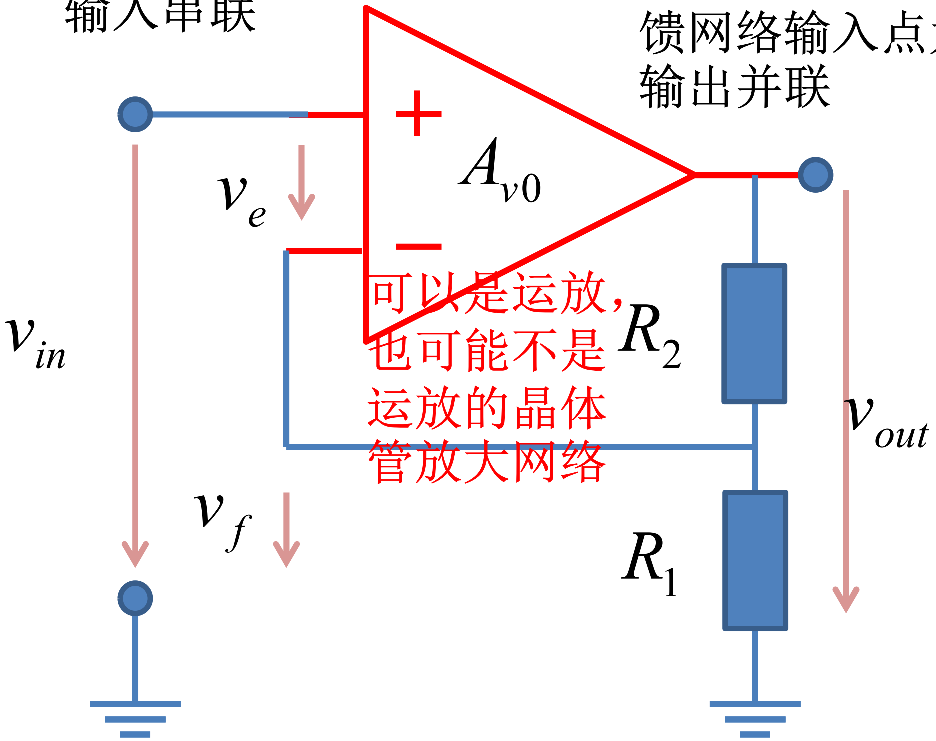
增益由电阻决定，负反馈屏蔽晶体管不稳定因素

*由运放形成的四种理想受控源分析

运放模块可以是任意的可提供高增益的晶体管放大网络

放大网络输入点和反馈网络输出点非一点：输入串联

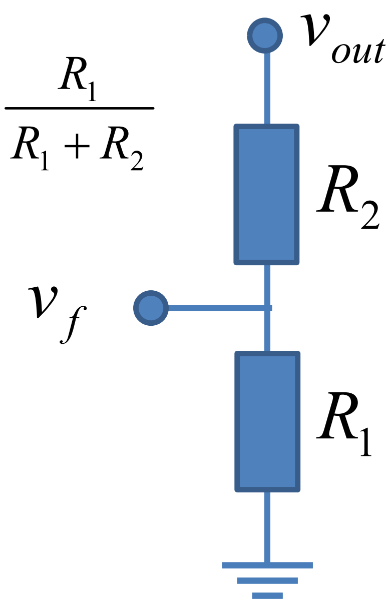
放大网络输出点和反馈网络输入点为一点：输出并联



串并负反馈：形成理想压控压源

反馈网络输入加电压源激励，反馈网络输出开路，获得电压反馈系数

$$F_v = \frac{v_f}{v_{out}} = \frac{R_1}{R_1 + R_2}$$



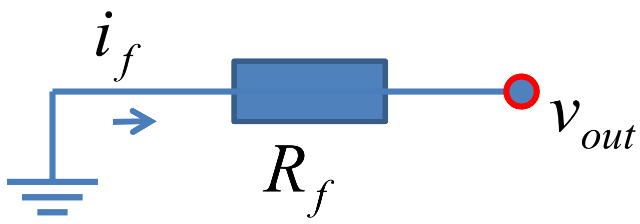
$$A_{vf} \approx \frac{1}{F_v} = 1 + \frac{R_2}{R_1}$$

$$v_{out} = \left(1 + \frac{R_2}{R_1}\right) v_{in}$$

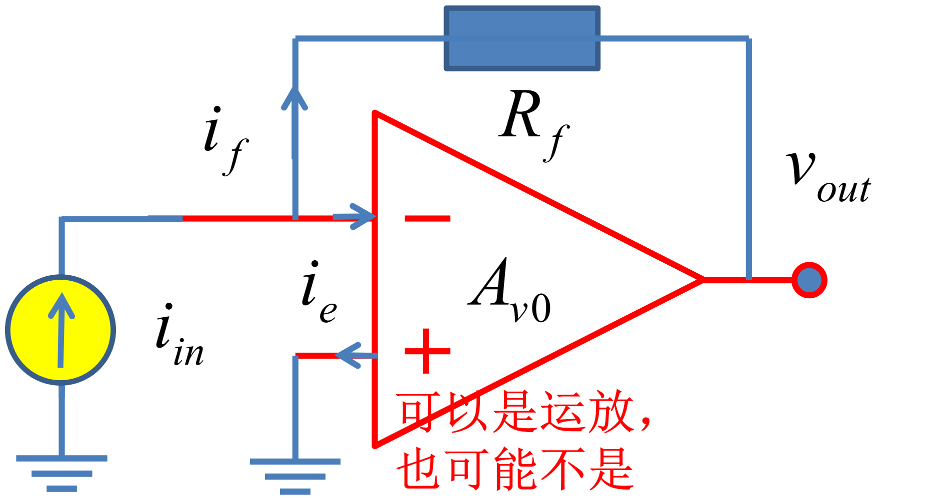
放大网络输入点和反馈网络输出点为一点：输入并联

放大网络输出点和反馈网络输入点为一点：输出并联

反馈网络输入加电压源激励，反馈网络输出短路，获得跨导反馈系数



$$G_F = \frac{i_f}{v_{out}} = -\frac{1}{R_f}$$



可以是运放，也可能不是运放的晶体管放大网络

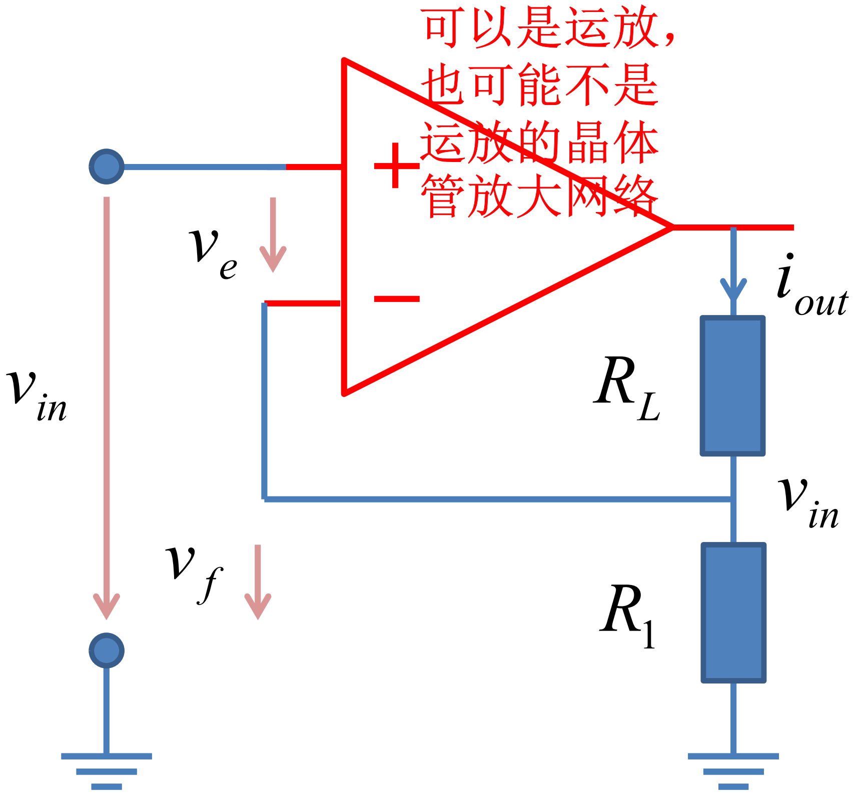
并并负反馈：形成理想流控压源

$$R_{mf} \approx \frac{1}{G_F} = -R_f$$

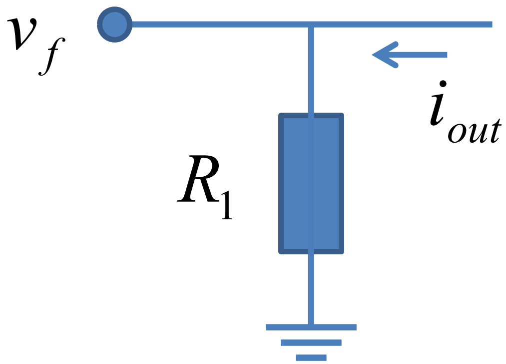
$$v_{out} = -R_f i_{in}$$

串串负反馈：形成理想压控流源

$$G_{mf} \approx \frac{1}{R_F} = \frac{1}{R_1} \qquad i_{out} = \frac{1}{R_1} v_{in}$$



反馈网络输入加电流源激励，反馈网络输出开路，获得跨阻反馈系数

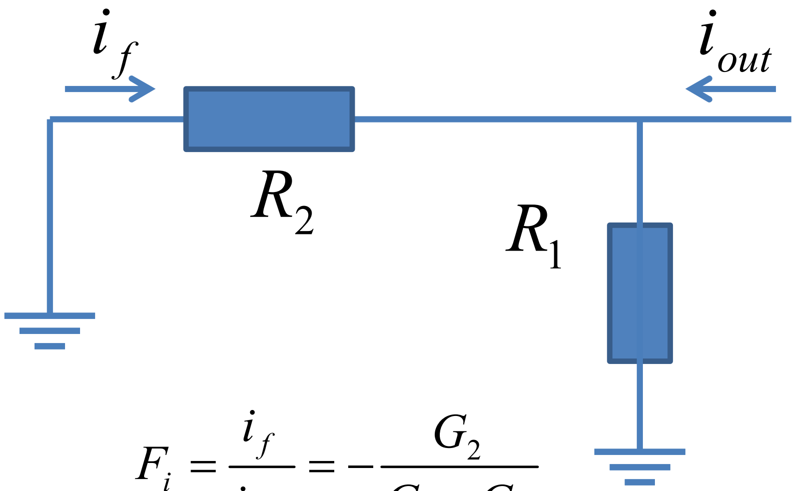


$$R_F \approx \frac{v_f}{i_{out}} = R_1$$

放大网络输入点和反馈网络输出点非一点：输入串联

放大网络输出点和反馈网络输入点非一点：输出串联

反馈网络输入加电流源激励，反馈网络输出短路，获得电流反馈系数



$$F_i = \frac{i_f}{i_{out}} = -\frac{G_2}{G_1 + G_2}$$

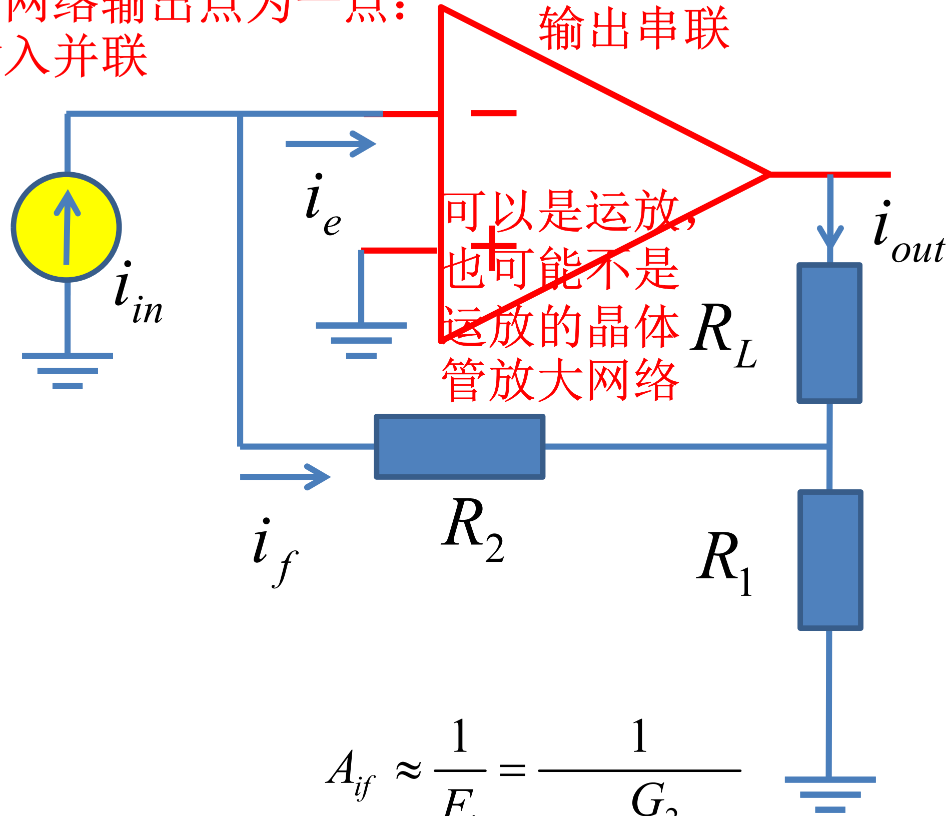
并串负反馈：形成理想流控流源

只需分析晶体管网络的电阻反馈网络，即可获得深度负反馈下的增益
前提假设：晶体管网络具有高增益

晶体管放大网络可能是运放，也可能不是

放大网络输入点和反馈网络输出点为一点：输入并联

放大网络输出点和反馈网络输入点非一点：输出串联



$$A_{if} \approx \frac{1}{F_i} = \frac{1}{-\frac{G_2}{G_1 + G_2}}$$

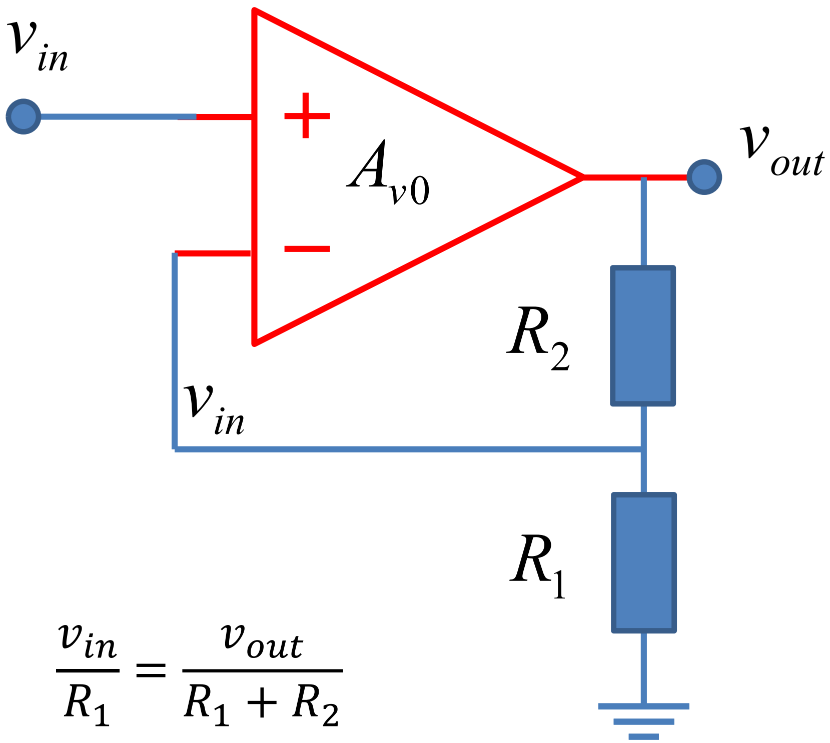
$$= -1 - \frac{G_1}{G_2} = -1 - \frac{R_2}{R_1}$$

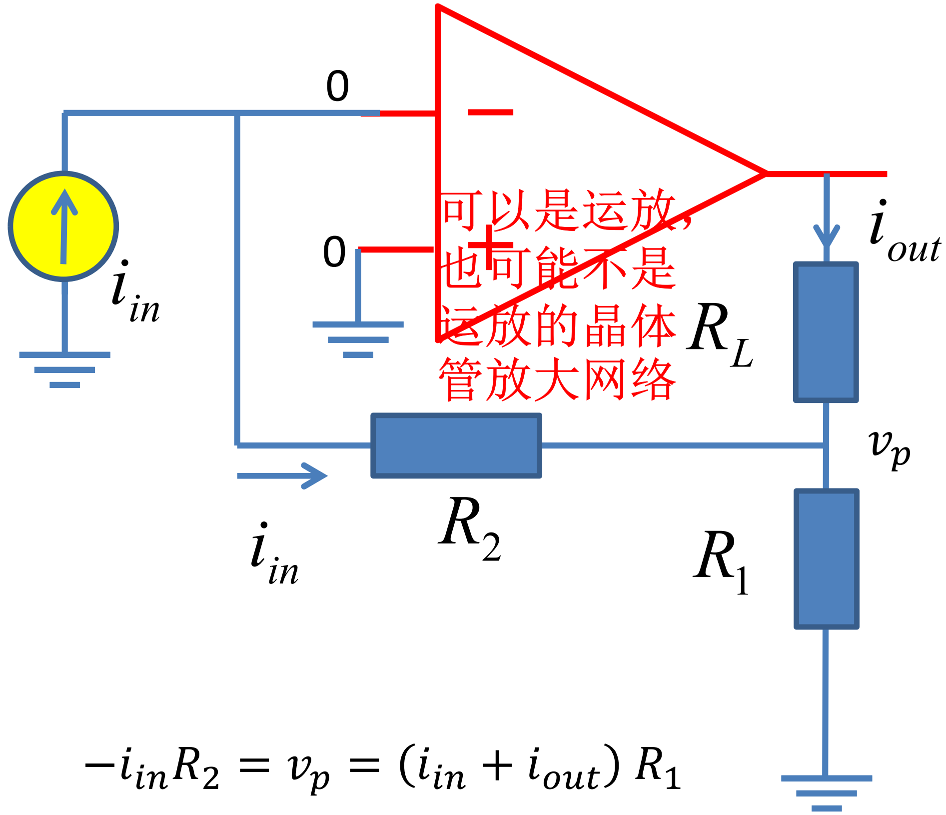
$$i_{out} = -\left(1 + \frac{R_2}{R_1}\right) i_{in}$$

运放电路分析

- 由于运放增益极高，因而只要确认运放是负反馈连接，无需负反馈分析过程，直接利用虚短、虚断进行分析即可
  - 我们对输入阻抗、输出阻抗不感兴趣
    - 要么极小趋于零，要么极大趋于无穷
  - 我们只对传输特性感兴趣
    - 虚短、虚断可以很快给出结果，无需负反馈放大器分析全套流程
      - 虚短、虚断本身就是深度负反馈条件满足下的极度抽象简化分析方法

虚短虚断分析





$$-i_{in}R_2 = v_p = (i_{in} + i_{out})\,R_1$$

$$\frac{v_{in}}{R_1} = \frac{v_{out}}{R_1 + R_2}$$

$$\frac{R_2}{R_1} = \frac{i_{in} + i_{out}}{-i_{in}}$$

$$A_v = \frac{v_{out}}{v_{in}} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$$

$$A_i = \frac{i_{out}}{i_{in}} = -1 - \frac{R_2}{R_1}$$