Lecture 26--Feedback, part 2

from **Microelectronic Circuits** Text

by Sedra and Smith

Oxford Publishing

课程纲要

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负反馈放大器设计的一些基本原则

1. **Sensing**. 反馈网络的设计必须对感兴趣的输出信号去sense，输出是电压信号，则并联感知（电压表）；输出是电流信号，则串联感知（电流表）
2. **Mixing.** 反馈回来的信号要与输入信号相减，如果信号是电压信号，则用戴维南形式表述，反馈信号与输入信号串联；如果信号是电流信号，则用诺顿形式表述，反馈信号与输入信号并联
3. **Feedback Topology**. 反馈拓扑结构的选择要看放大器的输入输出分别是什么信号
4. **输入输出阻抗。** 更接近理想
5. **量纲。** Aβ 是无量纲的

Amplifier Type	Appropriate Feedback Topology
Voltage	Series–Shunt
Transconductance	Series–Series
Current	Shunt–Series
Transresistance	Shunt–Shunt

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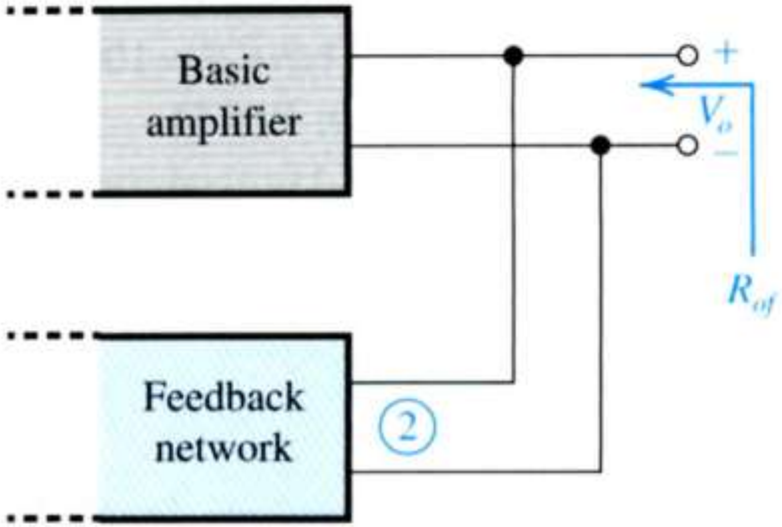
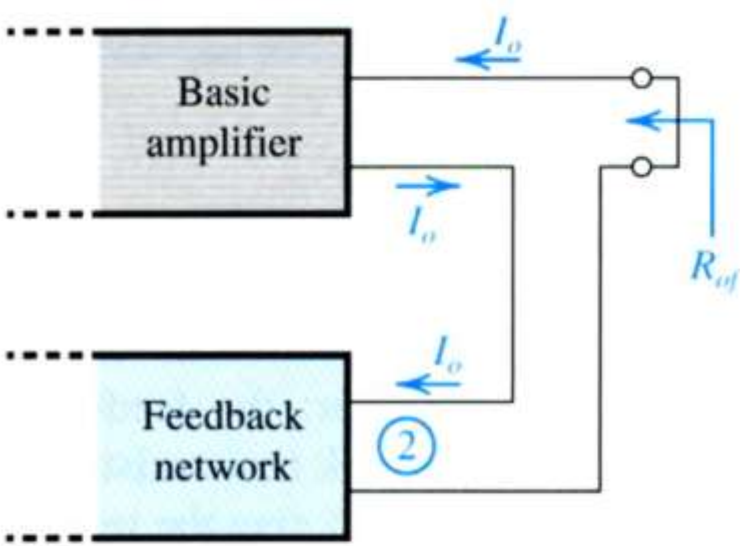
(a) Voltage (Shunt) Sensing



- Parallel (shunt) connection at output
- Applies for:
  - Voltage amplifiers
  - Transresistance amplifiers
- Decreases output resistance:

$$R_{of} = R_o / (1 + A\beta)$$

(b) Current (Series) Sensing



- Series connection at output
- Applies for:
  - Current amplifiers
  - Transconductance amplifiers
- Increases output resistance:

$$R_{of} = R_o (1 + A\beta)$$

Figure 11.19 The two methods of sensing.

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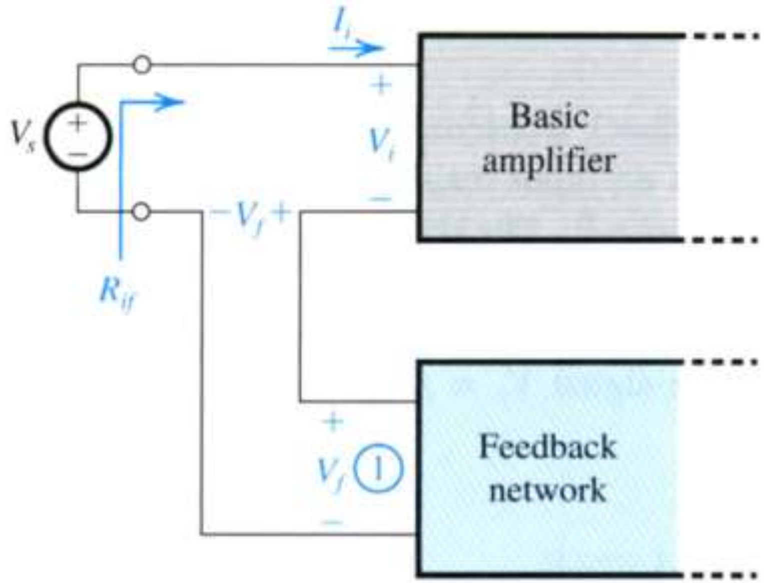
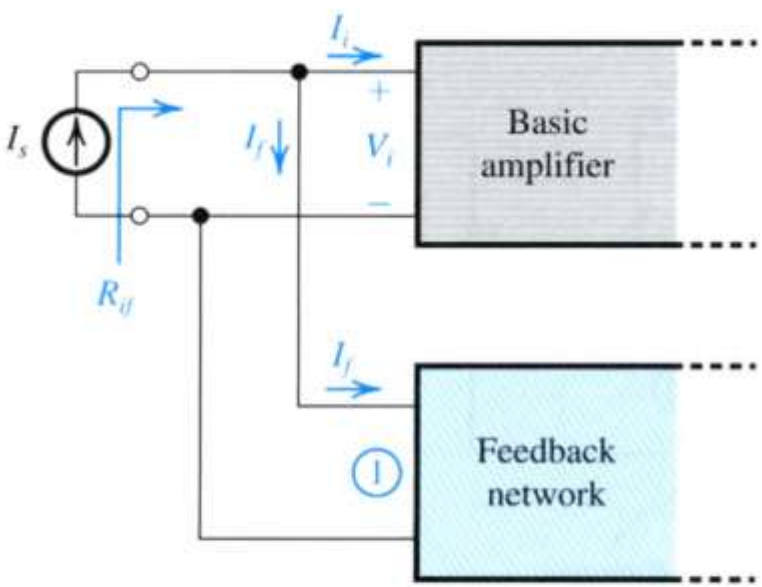
(a) Voltage (Series) Mixing



- Series connection at input
- Applies for:
  - Voltage amplifiers
  - Transconductance amplifiers
- Increases input resistance:
  $R_{if} = R_i(1 + A\beta)$

(b) Current (Shunt) Mixing



- Parallel (shunt) connection at input
- Applies for:
  - Current amplifiers
  - Transresistance amplifiers
- Decreases input resistance:
  $R_{if} = R_i/(1 + A\beta)$

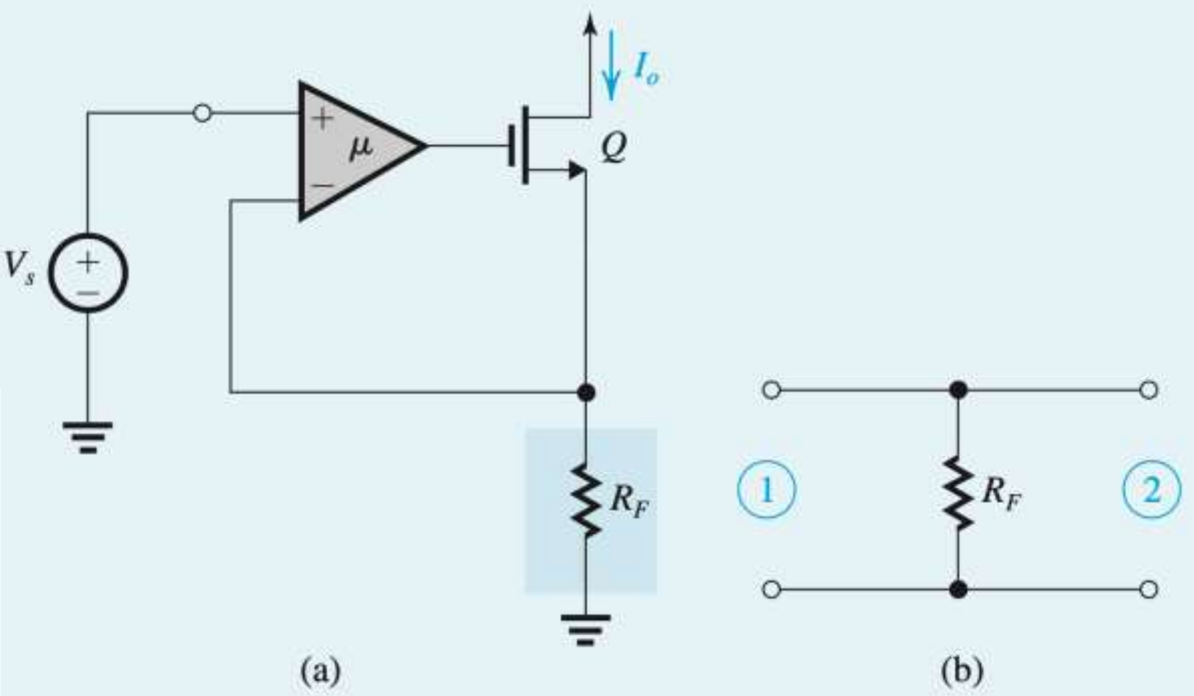
Figure 11.20 The two methods of mixing.

Example 11.6

跨导放大器（输入电压信号，输出电流信号），电流串联负反馈电路

Figure 11.17(a) shows a feedback transconductance amplifier utilizing an op amp together with an NMOS transistor. The feedback network consists of a resistor R_F that senses the output current I_o (recall that the drain and source currents of the MOSFET are equal) and provides a feedback voltage that is subtracted from V_s by means of the differencing action of the op-amp input. Observe that the feedback topology is series–series, which is uniquely appropriate for transconductance amplifiers.

(a) Find β and hence the closed-loop gain $A_f \equiv I_o/V_s$ obtained when $A\beta \gg 1$.

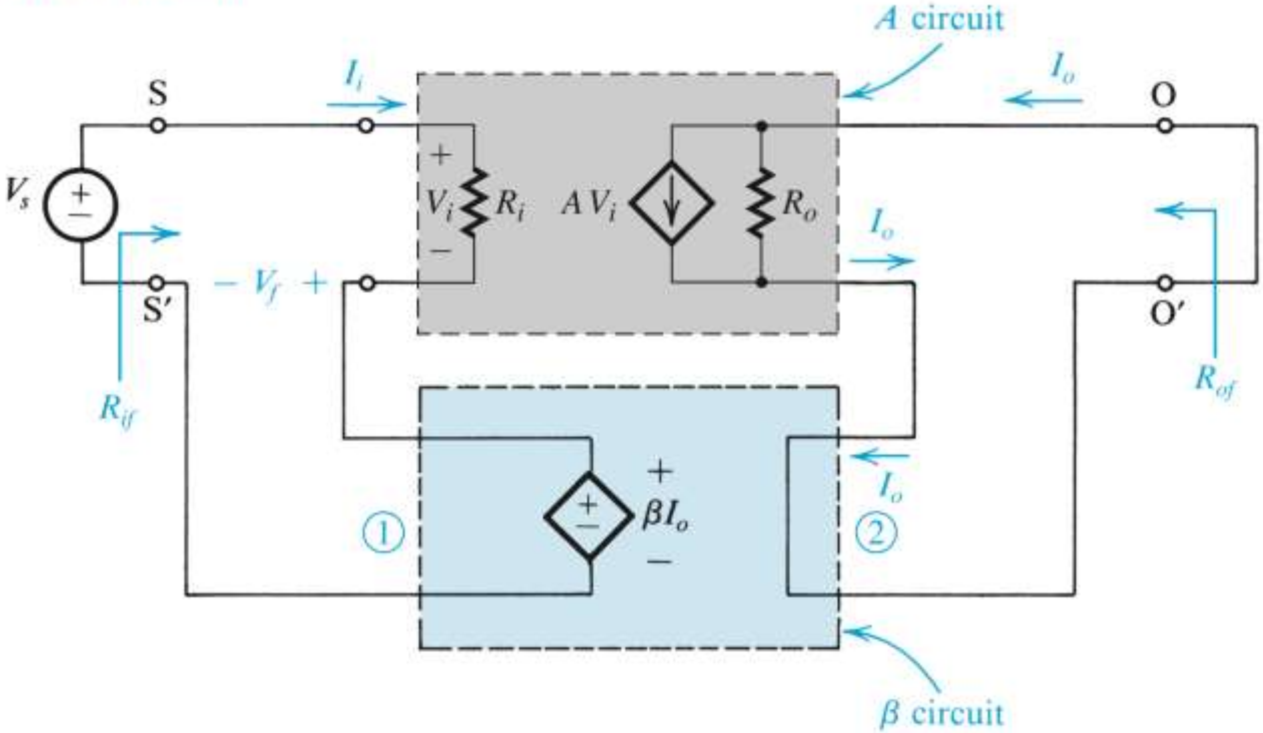


（a）destroy 端口①，开路；端口②施加电流，求端口①的响应电压，计算β

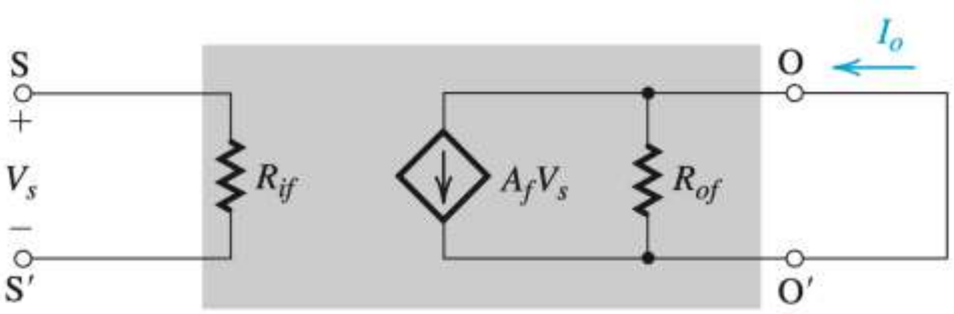
$$\beta = R_F$$

11.5.2 The Feedback Transconductance Amplifier (Series–Series) 电流串联负反馈电路（感知电流，返回电压）

(a) Ideal Structure



(b) Equivalent Circuit

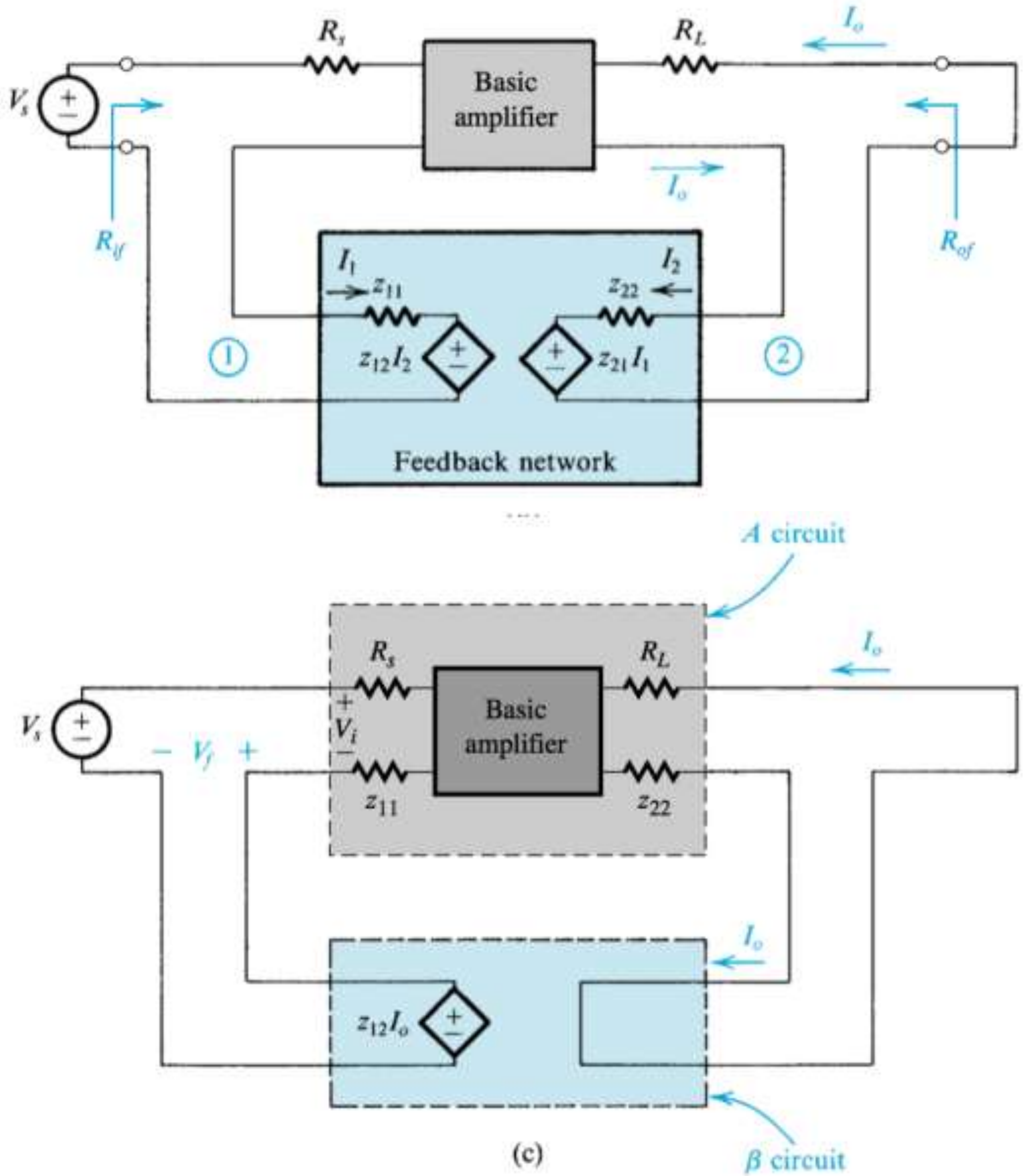


$$A_f = \frac{I_o}{V_s} = \frac{A}{1 + A\beta}$$

$$R_{if} = (1 + A\beta)R_i$$

$$R_{of} = (1 + A\beta)R_o$$

The Practical Case



将实际电路拆分成理想的β电路和A电路

第一步：计算反馈网络从两个端口看进去的等效电阻

原则是destroy the feedback

•串联 → 开路

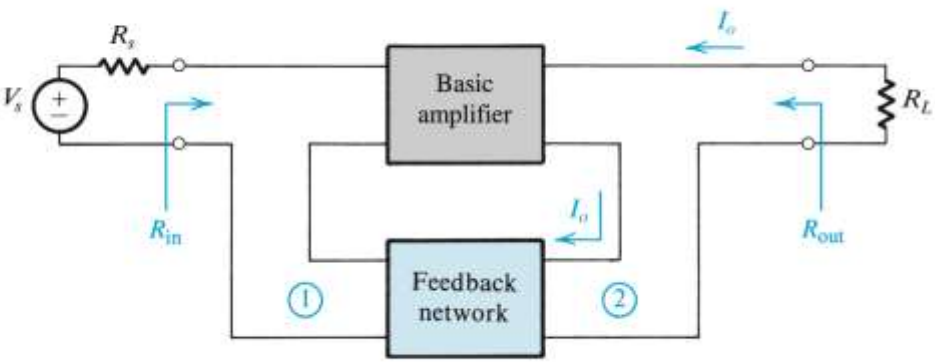
•并联 → 短路

•第二步：将等效电阻移到基本放大器，再把R_S和R_L也移进基本电路，构成新的基本电路（A电路）

•第三步：在反馈网络的②端口加激励，①端口destroy，求响应，计算β，获得新的β电路

$$\beta = z_{12} \equiv \left.\frac{V_1}{I_2}\right|_{I_1=0}$$

(a) General Structure



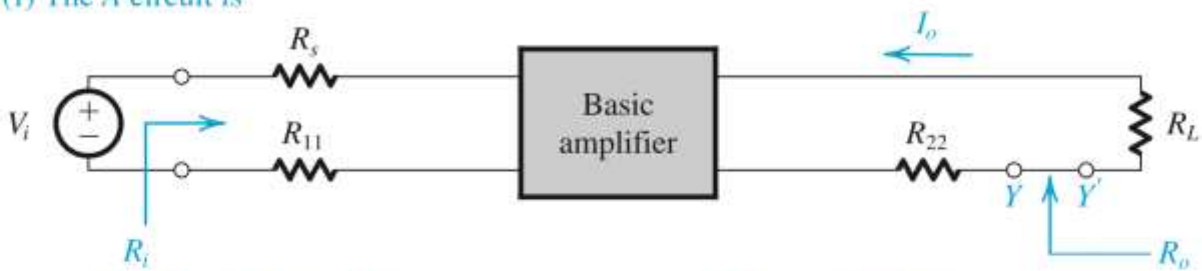
(c) Gain, Input, and Output Resistance

- Use the formulas in Fig. 11.18 to find A_f, R_{if}, and R_{of}.
- R_{in} and R_{out} can then be found from

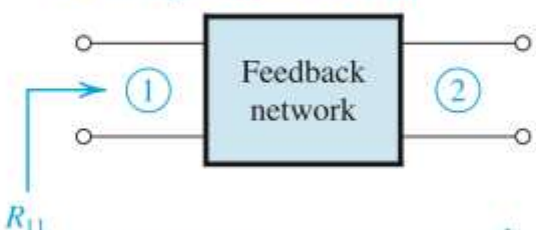
$$R_{in} = R_{if} - R_s$$
$$R_{out} = R_{of} - R_L$$

(b) Finding the A Circuit and β

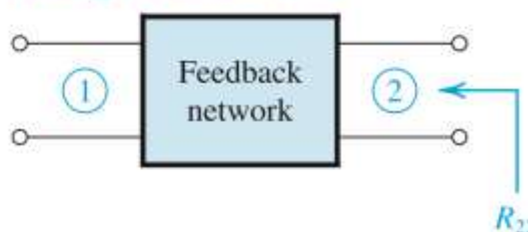
(i) The A circuit is



where R_{11} is obtained from

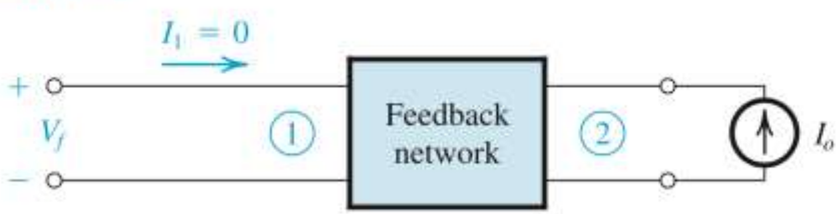


and R_{22} is obtained from



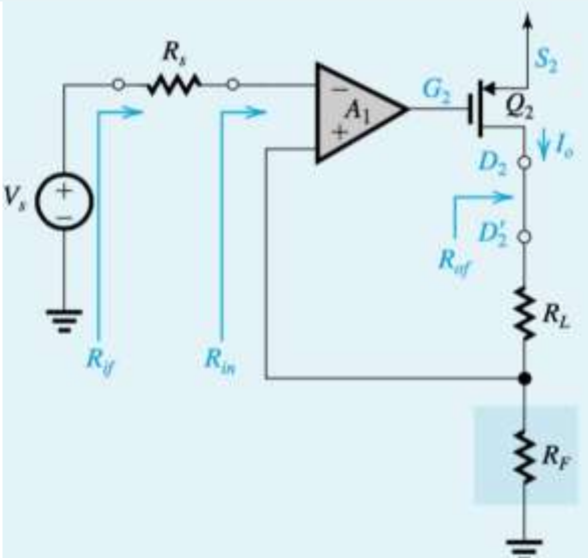
and the gain A is defined $A \equiv \dfrac{I_o}{V_i}$

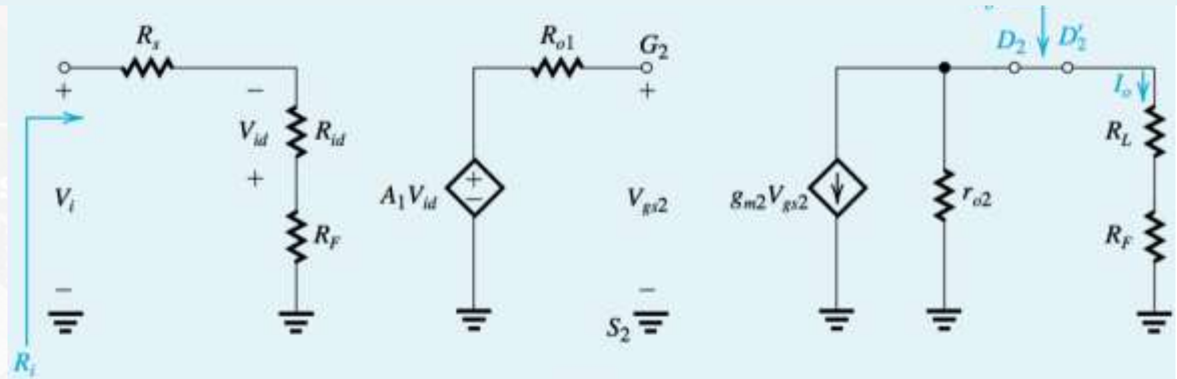
(ii) β is obtained from



$$\beta \equiv \left.\frac{V_f}{I_o}\right|_{I_1 = 0}$$

Figure 11.20(a) shows a feedback transconductance amplifier composed of a differential amplifier A_1 with an input differential resistance R_{id}, an open-circuit voltage gain A_1, and an output resistance R_{o1}, connected in cascade with a common source MOSFET Q_2 having a transconductance g_{m2} and an output resistance r_{o2}. Use the feedback-analysis method to determine the closed-loop transconductance $A_f \equiv I_o/V_s$, the input resistance R_{in}, and the output resistance R_{out}. The latter is the resistance seen between the terminals of R_L, looking back into the output loop.





(c)

①判断是电流串联型负反馈电路；

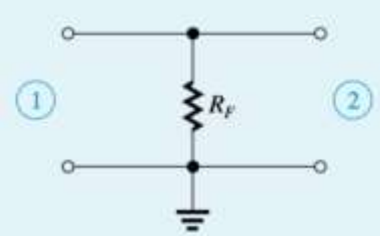
$$\beta = R_F$$

②拆分A电路和β电路，计算包含了z11，z22后的正向放大器A

$$A \equiv \frac{I_o}{V_i} = (A_1 g_{m2})\left(\frac{R_{id}}{R_{id}+R_s+R_F}\right)\left(\frac{r_{o2}}{r_{o2}+R_L+R_F}\right)$$

Usually $R_{id} \gg (R_s + R_F)$, $r_{o2} \gg (R_L + R_F)$

$$A \simeq A_1 g_{m2}$$



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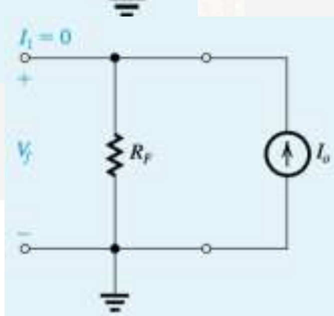

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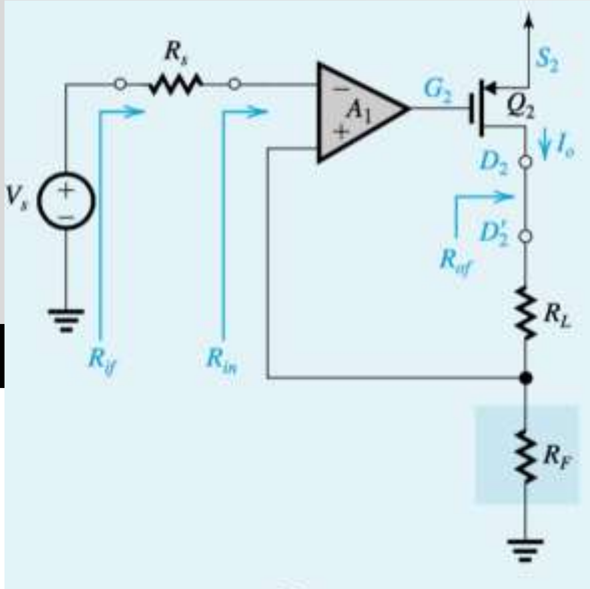
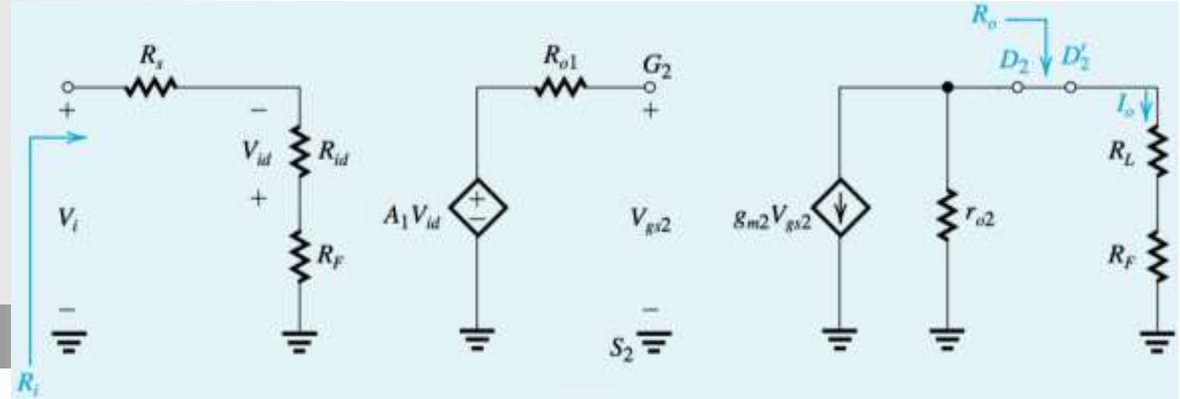


(a)



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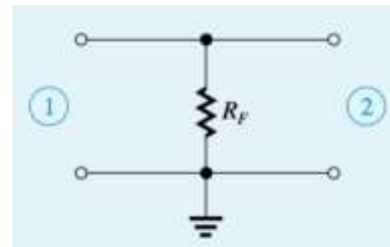

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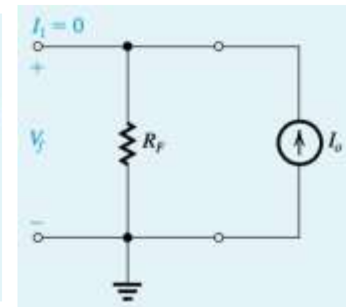


(d)

③计算闭环增益

$$A\beta = (A_1 g_{m2} R_F)\left(\frac{R_{id}}{R_{id}+R_s+R_F}\right)\left(\frac{r_{o2}}{r_{o2}+R_L+R_F}\right)$$

$$\simeq A_1 g_{m2} R_F$$

$$A_f = \frac{A}{1+A\beta} \simeq \frac{A_1 g_{m2}}{1+A_1 g_{m2} R_F} \simeq \frac{1}{R_F}$$

④计算I/O阻抗

$$R_i = R_s + R_{id} + R_F$$

$$R_{if} = R_i(1+A\beta) \simeq R_s + R_{id} + R_F + A_1 g_{m2} R_F R_{id} \Rightarrow R_{\text{in}} = R_{id} + R_F + A_1 g_{m2} R_F R_{id}$$

$$\simeq R_{id}(1+A_1 g_{m2} R_F)$$

$$R_o = r_{o2} + R_L + R_F$$

$$R_{of} = R_o(1+A\beta) \Rightarrow R_{\text{out}} = r_{o2} + R_F + A_1 g_{m2} R_F r_{o2} \simeq r_{o2}(1+A_1 g_{m2} R_F)$$

$$= (r_{o2}+R_L+R_F)(1+A\beta)$$

$$= r_{o2} + R_L + R_F + A\beta(r_{o2}+R_L+R_F) \simeq r_{o2} + R_L + R_F + A_1 g_{m2} R_F r_{o2}$$

Example 11.8

Because negative feedback extends the amplifier bandwidth, it is commonly used in the design of broadband amplifiers. One such amplifier is the MC1553. Part of the circuit of the MC1553 is shown in Fig. 11.21(a). The circuit shown (called a **feedback triple**) is composed of three gain stages with series–series feedback provided by the network composed of R_{E1}, R_F, and R_{E2}.

Observe that the feedback network samples the emitter current I_o of Q_3, and thus I_o is the output quantity of the feedback amplifier. However, practically speaking, I_o is rather difficult to utilize. Thus it is usual to take as the output I_c, the collector current of Q_3. This current is of course almost equal to I_o; $I_c = \alpha I_o$. Thus, as a transconductance amplifier with I_c as the output current, the output resistance of interest is that labeled R_{out} in Fig. 11.21(a). In some applications, I_c is passed through a load resistance, such as R_{C3}, and the voltage V_o is taken as the output. Assume that the bias circuit, which is not shown, establishes $I_{C1} = 0.6$ mA, $I_{C2} = 1$ mA, and $I_{C3} = 4$ mA. Also assume that for all three transistors,[5] $h_{fe} = 100$ and $r_o = \infty$. 因为负反馈分析里，ß指反馈网络的系数，所以三极管的ß用h_{fe}表示

(a) Anticipating that the loop gain will be large, find an approximate expression and value for the closed-loop gain $A_f \equiv I_o/V_s$ and hence for I_c/V_s. Also find V_o/V_s. 深反馈近似，可以得出增益，但得不出I/O阻抗

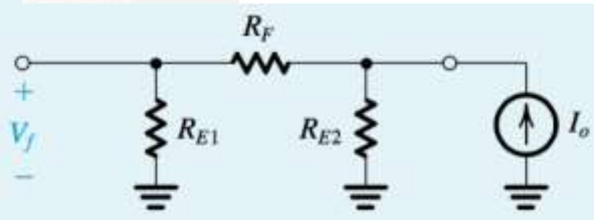
(b) Use feedback analysis to find A, β, A_f, V_o/V_s, R_{in}, and R_{out}. For the calculation of R_{out}, assume that r_o of Q_3 is 25 kΩ. 拆分计算A、ß，可以得出增益，也可得出I/O阻抗

$$\beta \equiv \frac{V_f}{I_o} = \frac{R_{E2}}{R_{E2}+R_F+R_{E1}} \times R_{E1} = 11.9\ \Omega$$

$$A_f \equiv \frac{I_o}{V_s} \simeq \frac{1}{\beta} = 84\ \text{mA/V}$$

$$\frac{I_c}{V_s} \simeq \frac{I_o}{V_s}$$

$$\frac{V_o}{V_s} = \frac{-I_c R_{C3}}{V_s} = -84 \times 0.6 = -50.4\ \text{V/V}$$



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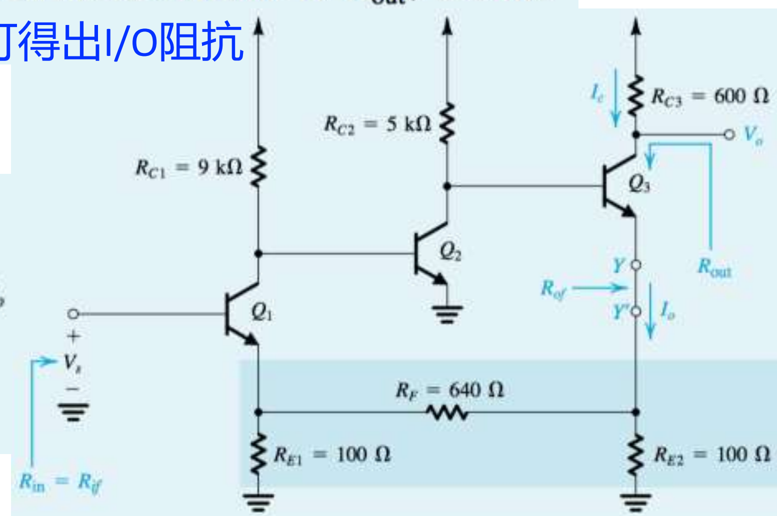
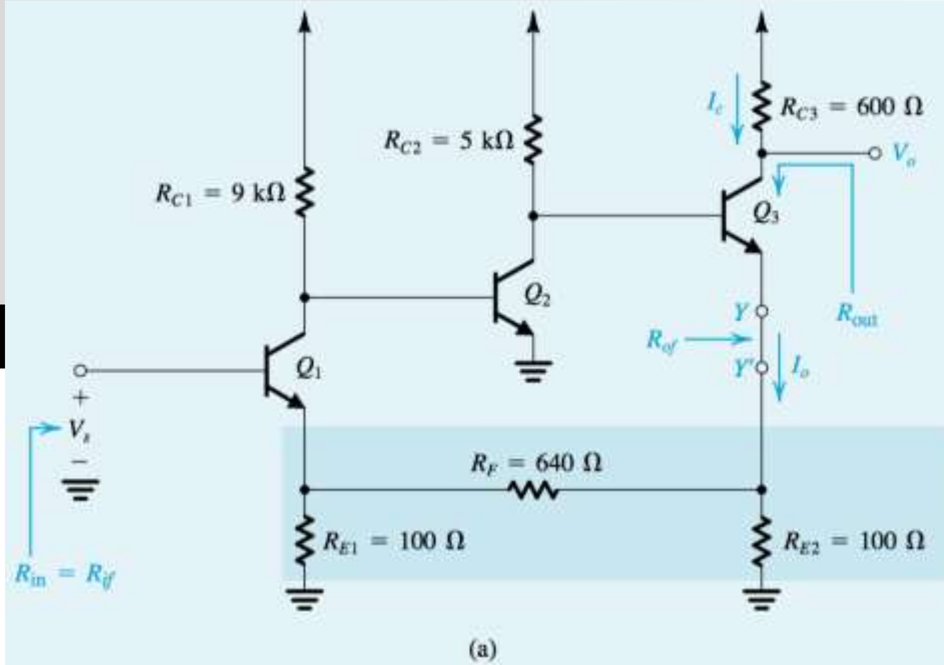


(a)

级联计算



$$\frac{V_{c1}}{V_i} = \frac{-\alpha_1(R_{C1} \parallel r_{\pi 2})}{r_{e1} + [R_{E1} \parallel (R_F + R_{E2})]}$$

$$\frac{V_{c2}}{V_{c1}} = -g_{m2}\{R_{C2} \parallel (h_{fe}+1)[r_{e3} + (R_{E2} \parallel (R_F + R_{E1}))]\}$$

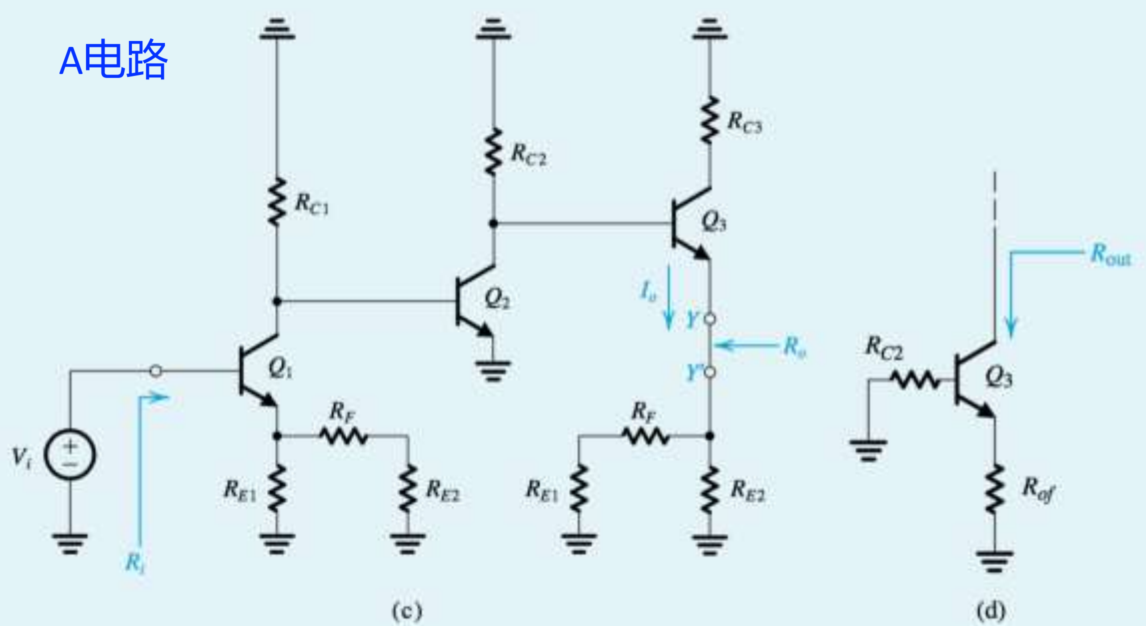
$$\frac{I_o}{V_{c2}} = \frac{I_{e3}}{V_{b3}} = \frac{1}{r_{e3} + (R_{E2} \parallel (R_F + R_{E1}))}$$

$$A \equiv \frac{I_o}{V_i} = 20.7\ \text{A/V}$$

$$A_f \equiv \frac{I_o}{V_s} = \frac{A}{1 + A\beta} = 83.7\ \text{mA/V}$$

$$\frac{V_o}{V_s} = -A_f R_{C3}$$

A电路



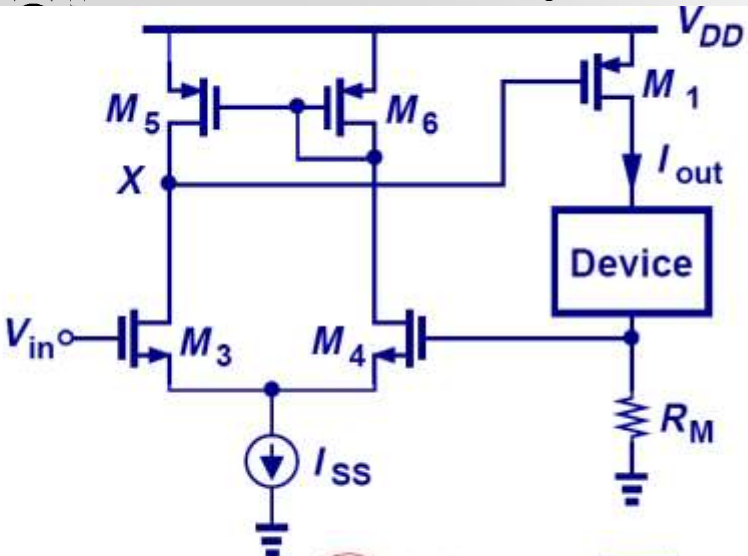
$$R_{in} = R_{if} = R_i(1 + A\beta)$$

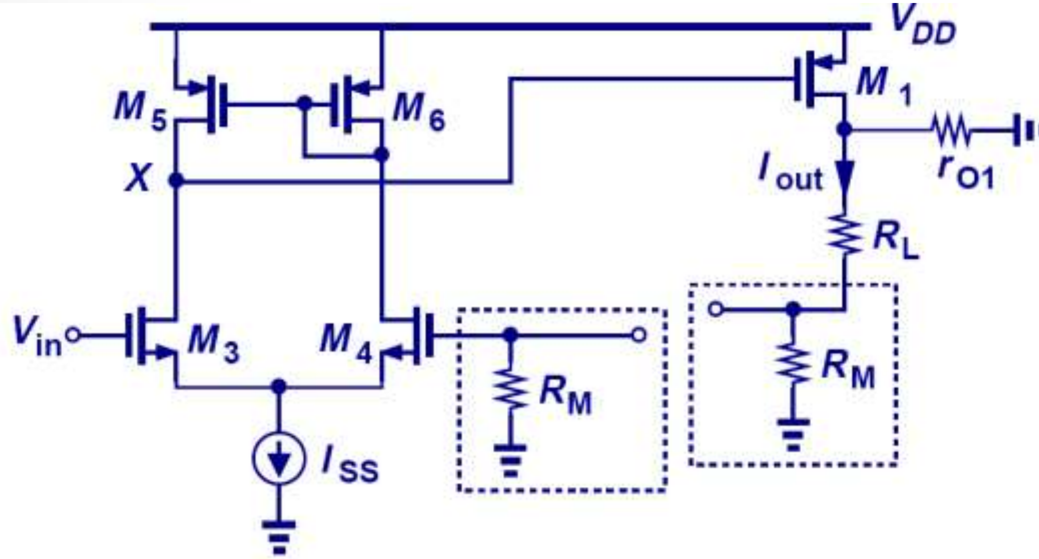
$$R_i = (h_{fe}+1)[r_{e1} + (R_{E1} \parallel (R_F + R_{E2}))]$$

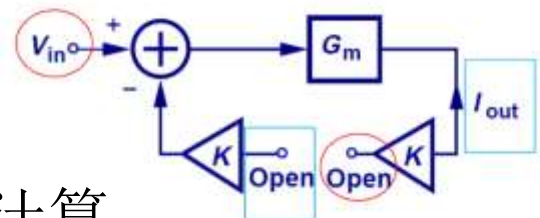
$$R_{of} = R_o(1 + A\beta)$$

$$R_o = [R_{E2} \parallel (R_F + R_{E1})] + r_{e3} + \frac{R_{C2}}{h_{fe}+1}$$

Breaking the Loop
Example V

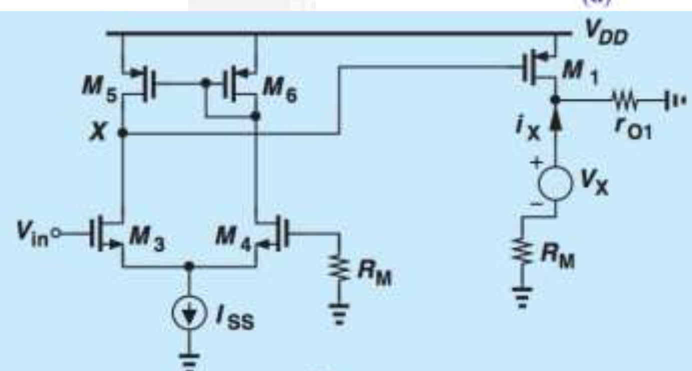






(d)

输出阻抗计算



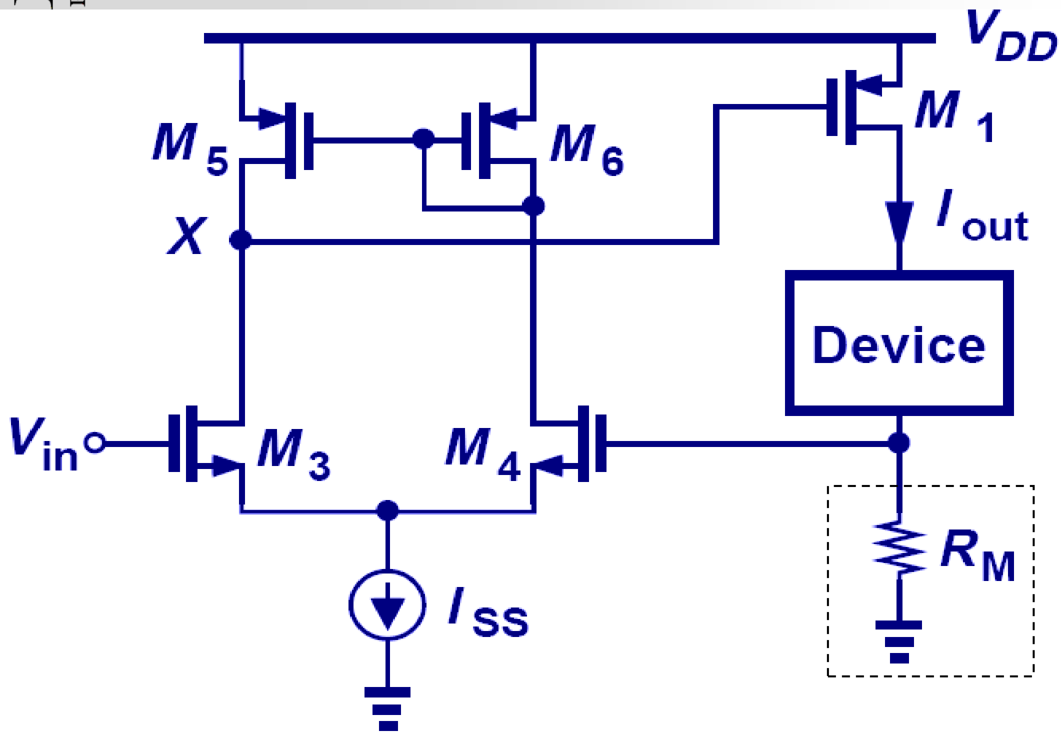
(c)

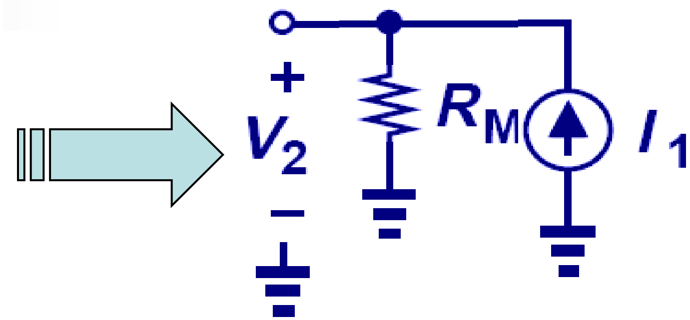
$$\frac{I_{out}}{V_{in}}\Big|_{open}=\frac{g_{m3}(r_{O3}\,||\,r_{O5})g_{m1}r_{O1}}{r_{O1}+R_L+R_M}$$

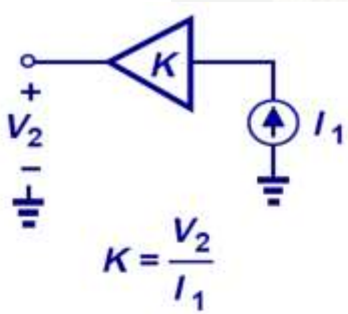
$$R_{in,open}=\infty$$

$$R_{out,open}=r_{O1}+R_M$$

Feedback Factor Example V







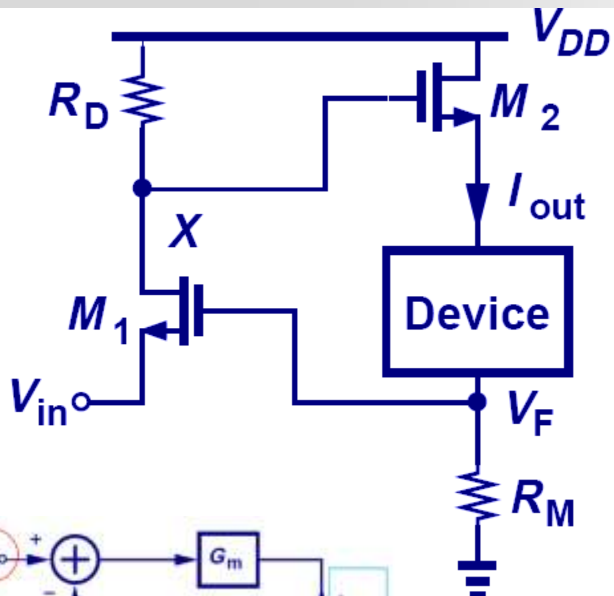
$$K = R_M$$

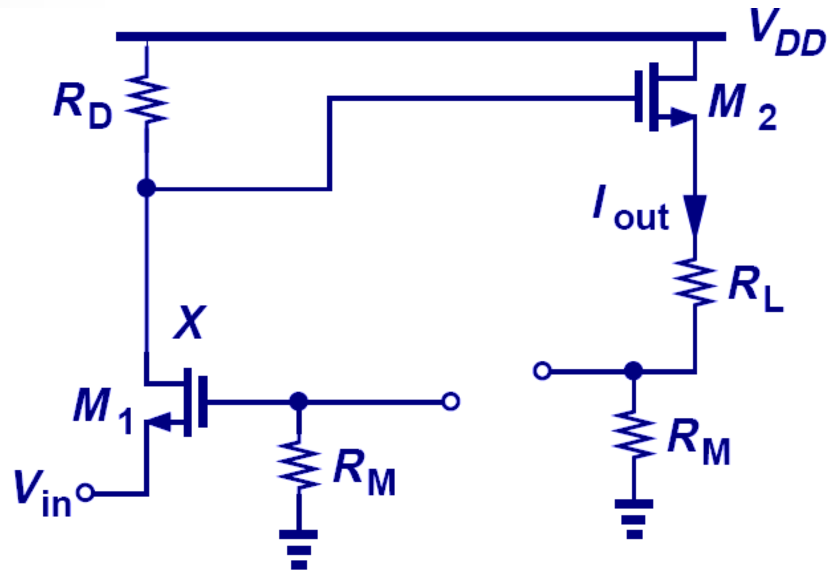
$$(I_{out}/V_{in}|_{closed}) = (I_{out}/V_{in}|_{open})/[1 + K(I_{out}/V_{in})|_{open}]$$

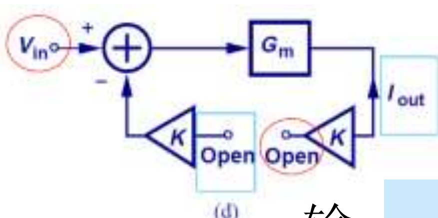
$$R_{in,closed} = \infty$$

$$R_{out,closed} = R_{out,open}[1 + K(I_{out}/V_{in})|_{open}]$$

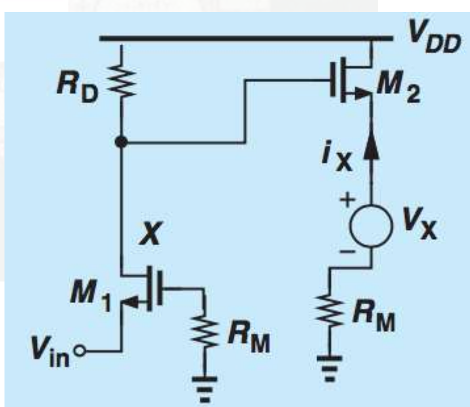
Breaking the Loop
Example VI







输出阻抗计算



$$\frac{I_{out}}{V_{in}}\Big|_{open} = \frac{g_{m1}R_D}{R_L + R_M + 1/g_{m2}}$$

$$R_{in,open} = 1/g_{m1}$$

$$R_{out,open} = (1/g_{m2}) + R_M$$

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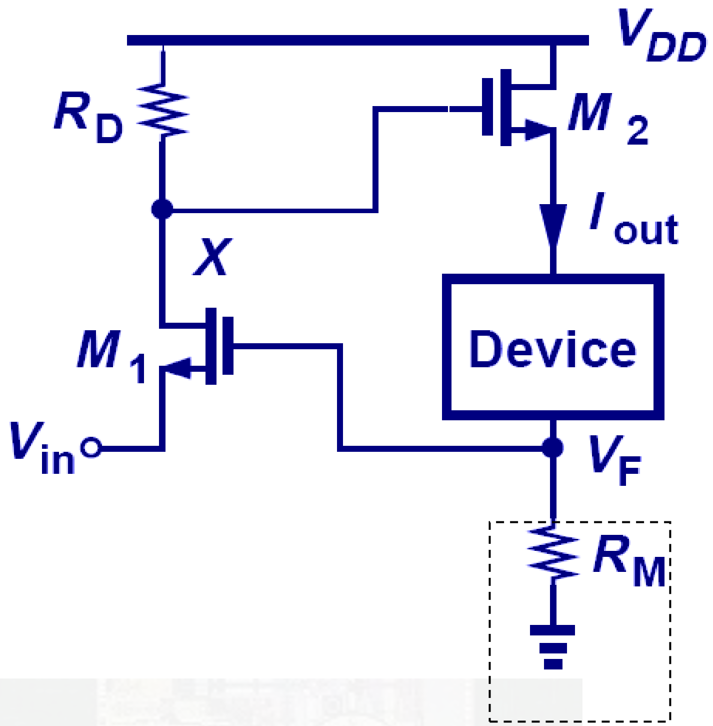
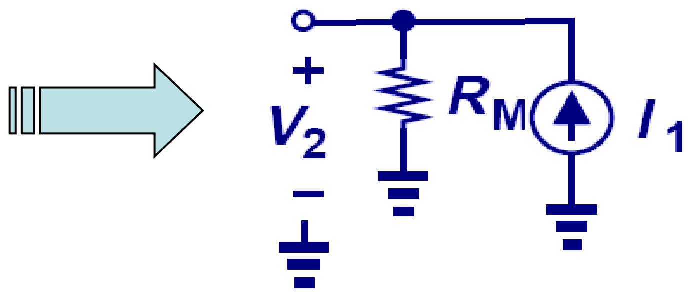
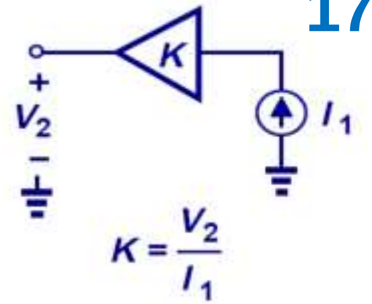
Feedback Factor Example VI







$$K = R_M$$

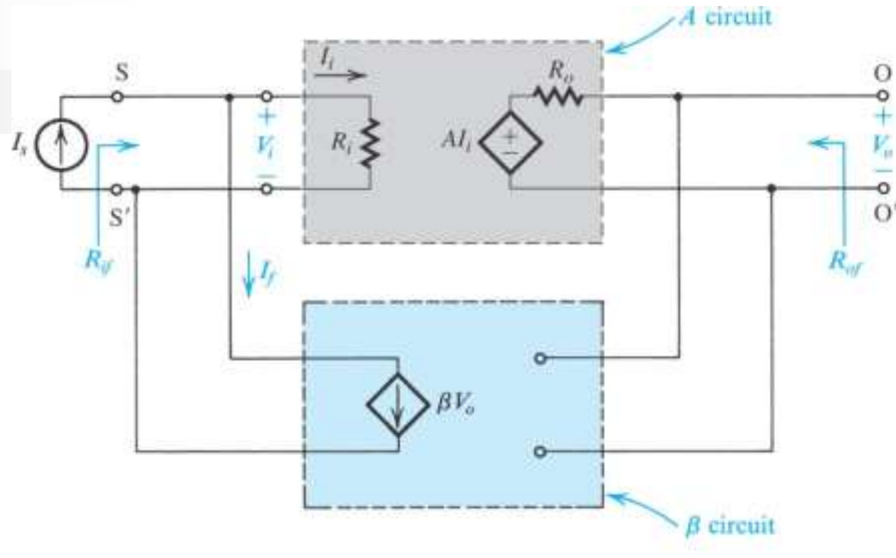
$$(I_{out}/V_{in}|_{closed}) = (I_{out}/V_{in}|_{open})/[1 + K(I_{out}/V_{in})|_{open}]$$

$$R_{in,closed} = R_{in,open}[1 + K(I_{out}/V_{in})|_{open}]$$

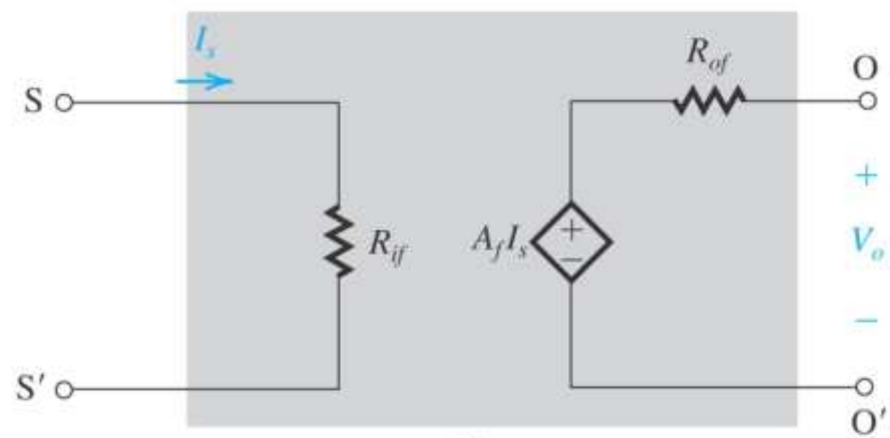
$$R_{out,closed} = R_{out,open}[1 + K(I_{out}/V_{in})|_{open}]$$

11.5.3. The Feedback Transresistance Amplifier

电压并联负反馈（感知电压，反馈电流）



(a)



(b)

理想的“电压并联负反馈”

① 正向放大电路（A circuit）具有输入电阻 R_i，输出电阻 R_o，开环增益 A

②反馈网络（β circuit）具有反馈因子 β　$I_f = \beta V_o$

③闭环增益：

$$A_f \equiv \frac{V_o}{I_s} = \frac{A}{1 + A\beta}$$

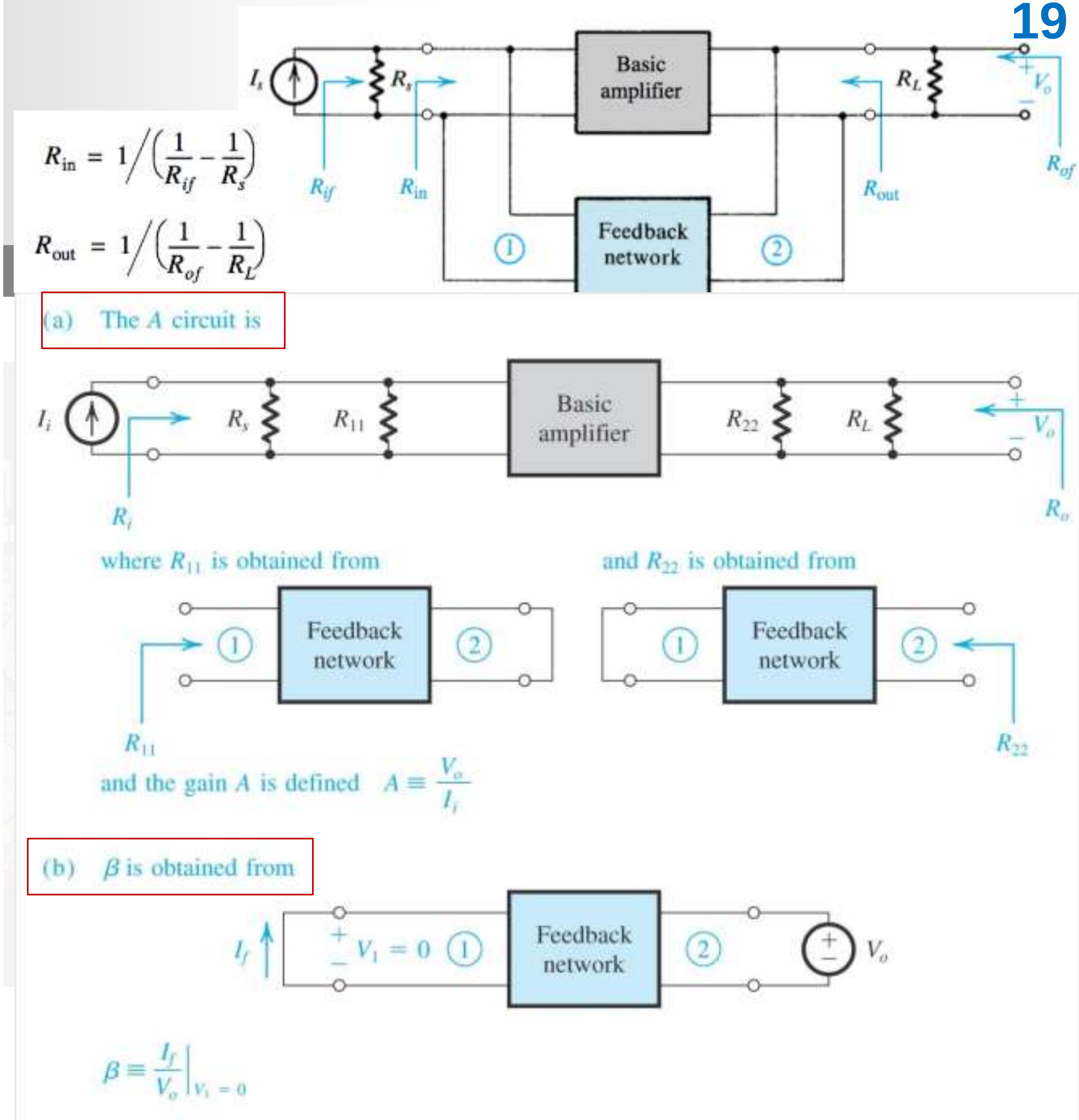
④闭环输入电阻降低：

$$R_{if} = \frac{R_i}{1 + A\beta}$$

⑤闭环输出电阻降低

$$R_{of} = \frac{R_o}{1 + A\beta}$$

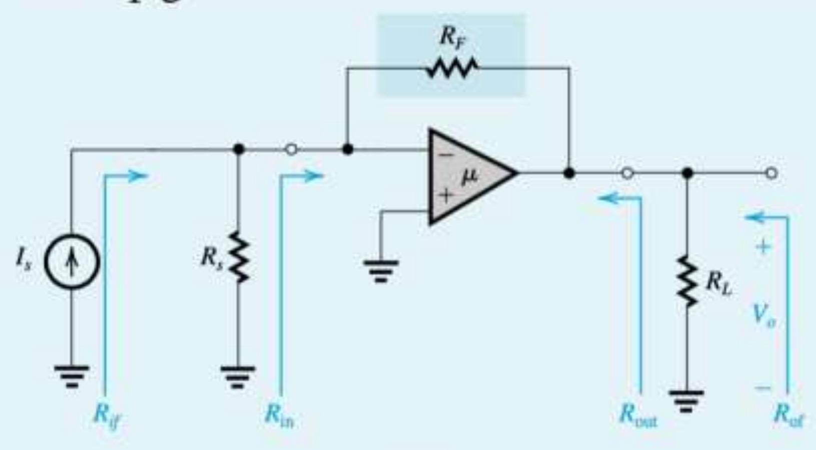
- 对于一个实际的负反馈电路，我们的目标：finding A & β；
- 求反馈网络①端口向右看的等效电阻R_{11}（此时②端口并联到主电路，destroy并联，故②端口短路）；
- 求反馈网络②端口向左看的等效电路R_{22}，同理，①端口短路；
- 将R_{11}和R_{22}包含进主电路，形成 A 电路，分别计算A及β



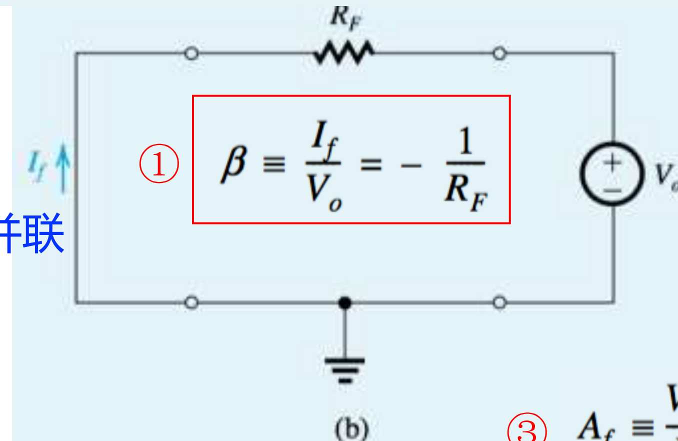
Example 11.9

Figure 11.24(a) shows a feedback transresistance amplifier. It is formed by connecting a resistance R_F in the negative-feedback path of a voltage amplifier with gain μ, an input resistance R_{id}, and an output resistance r_o. The amplifier μ can be implemented with an op amp, a simple differential amplifier, a single-ended inverting amplifier, or, in the limit, a single-transistor CE or CS amplifier. The latter case will be considered in Exercise 11.18. Of course, the higher the gain μ, the more ideal the characteristics of the feedback transresistance amplifier will be, simply because of the concomitant increase in loop gain.

感知电压，返回电流



destroy并联



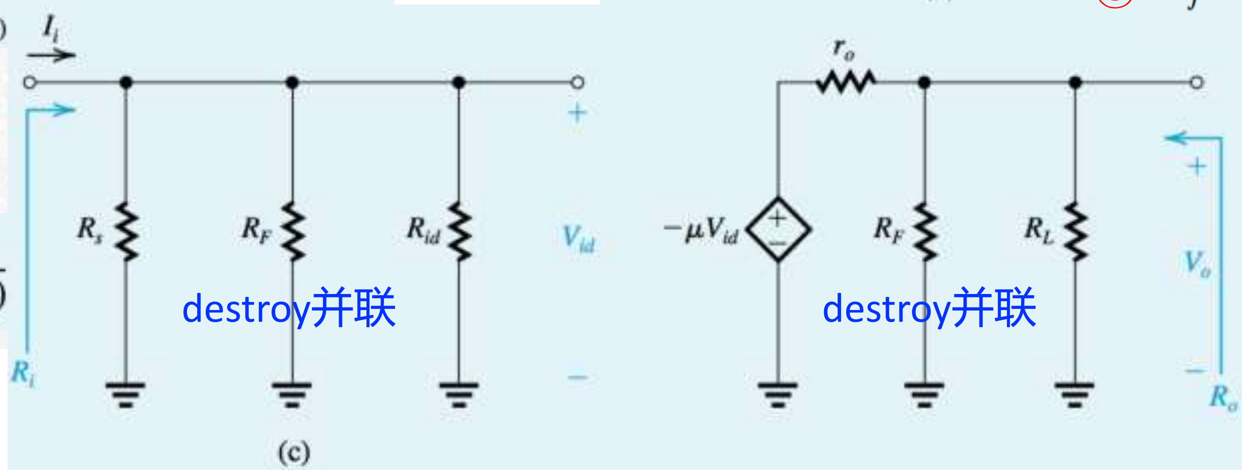
① $$\boxed{\beta \equiv \frac{I_f}{V_o} = -\frac{1}{R_F}}$$

③ $$A_f \equiv \frac{V_o}{I_s} = \frac{A}{1+A\beta}$$

② $$R_i = R_{id} \parallel R_F \parallel R_s$$

$$R_o = r_o \parallel R_F \parallel R_L$$

$$A \equiv \frac{V_o}{I_i} = -\mu R_i \frac{(R_F \parallel R_L)}{r_o + (R_F \parallel R_L)}$$

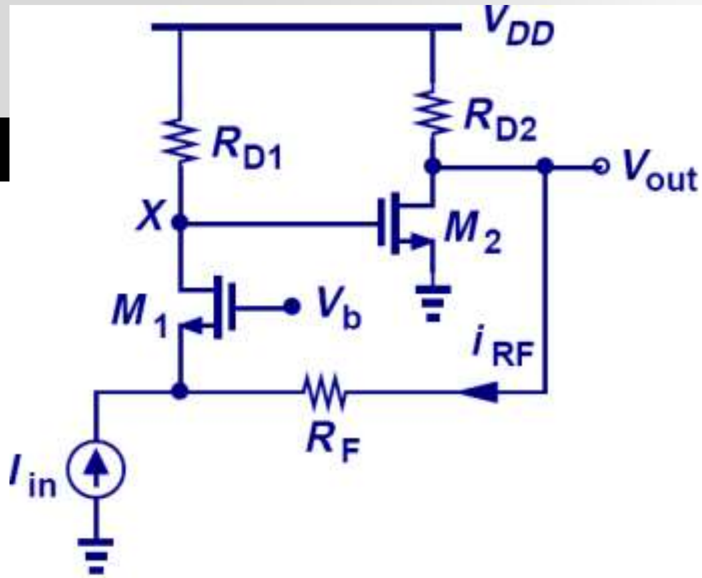


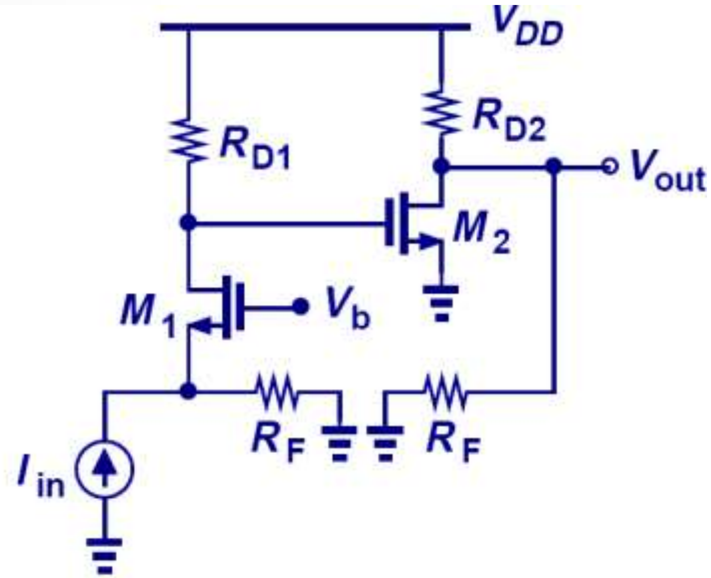
$$R_{if} = \frac{R_i}{1+A\beta}$$

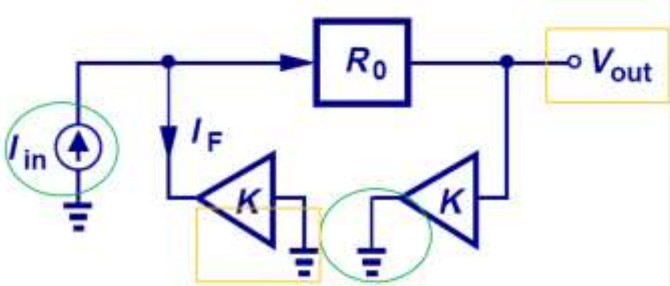
$$R_{of} = \frac{R_o}{1+A\beta}$$

Figure 11.24 (a) A feedback transresistance amplifier; (b) the β circuit; (c) determining β; (d) the A circuit.

Breaking the Loop Example IV







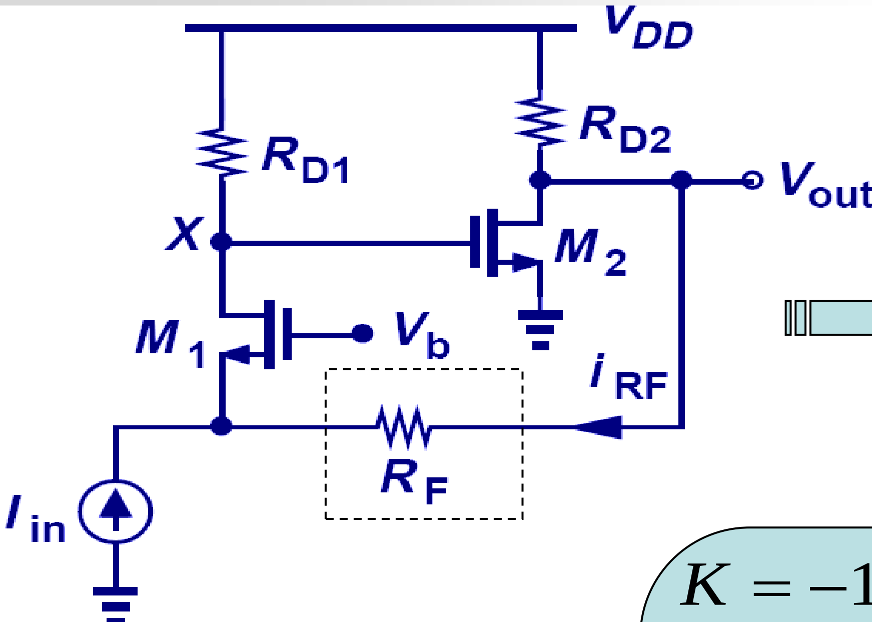
(b)

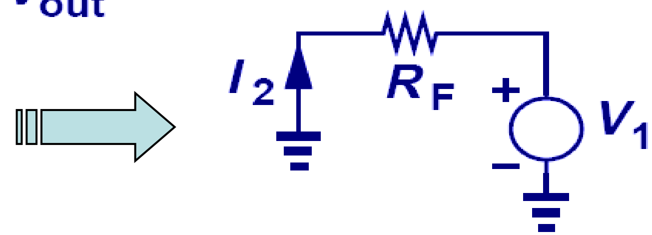
$$\frac{V_{out}}{I_{in}}\Big|_{open} = \frac{R_F R_{D1}}{R_F + \dfrac{1}{g_{m1}}} \cdot [-g_{m2}(R_{D2} \parallel R_F)]$$

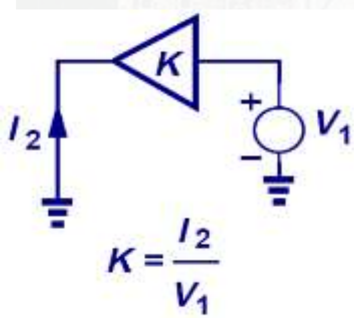
$$R_{in,open} = \frac{1}{g_{m1}} \parallel R_F$$

$$R_{out,open} = R_{D2} \parallel R_F$$

Feedback Factor Example IV







$$K = -1/R_F$$

$$\frac{V_{out}}{I_{in}}\Big|_{closed} = \frac{V_{out}}{I_{in}}\Big|_{open} / (1 + K\frac{V_{out}}{I_{in}}\Big|_{open})$$

$$R_{in,closed} = R_{in,open} / (1 + K\frac{V_{out}}{I_{in}}\Big|_{open})$$

$$R_{out,closed} = R_{out,open} / (1 + K\frac{V_{out}}{I_{in}}\Big|_{open})$$

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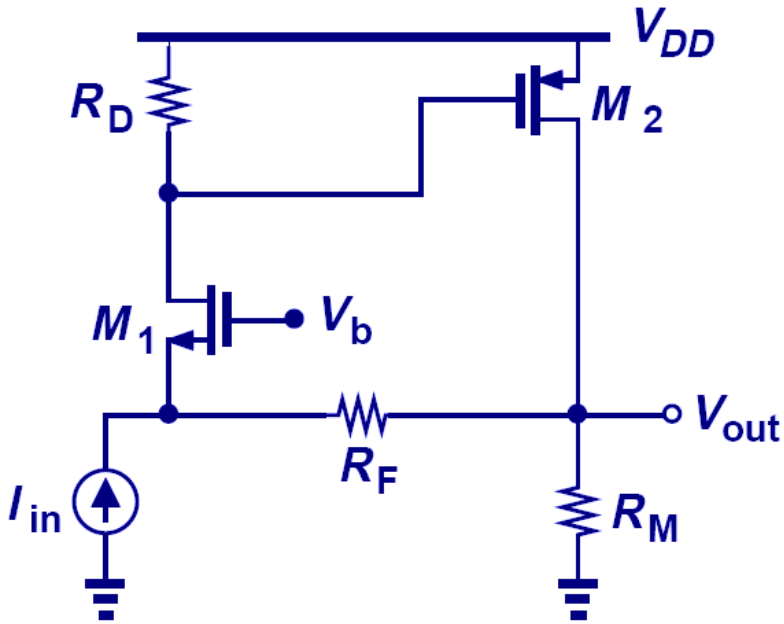
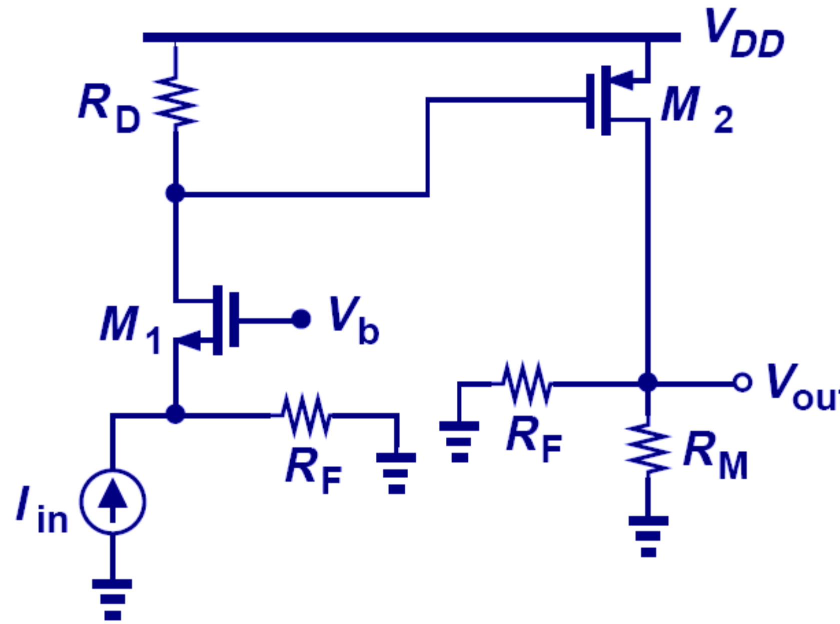
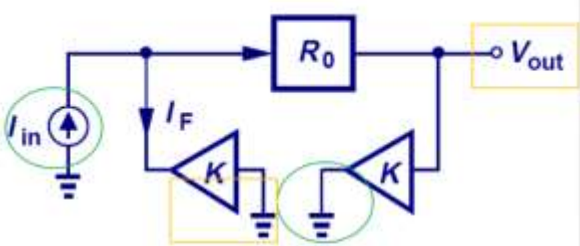
Breaking the Loop Example VIII







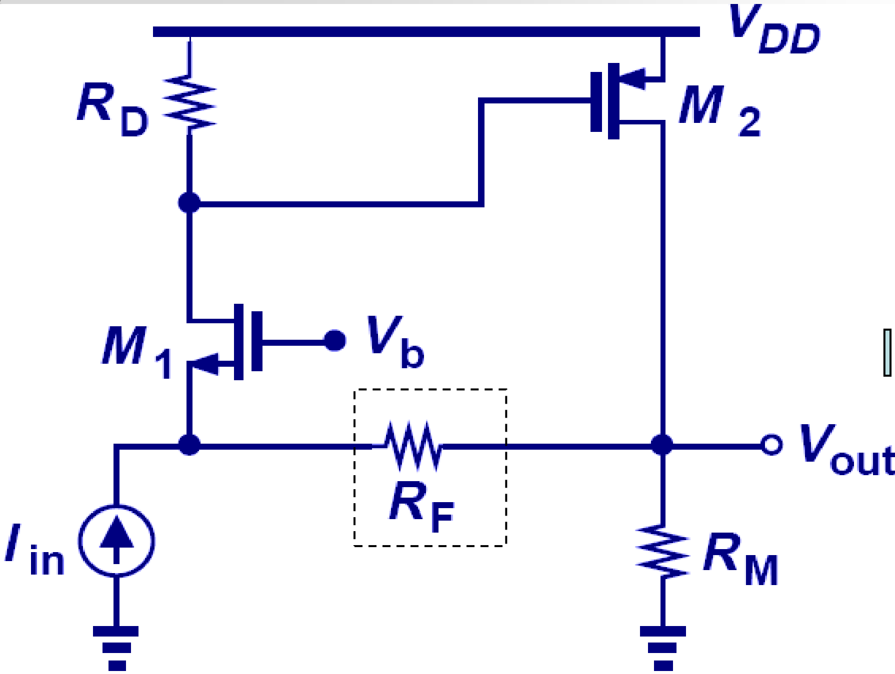
(b)

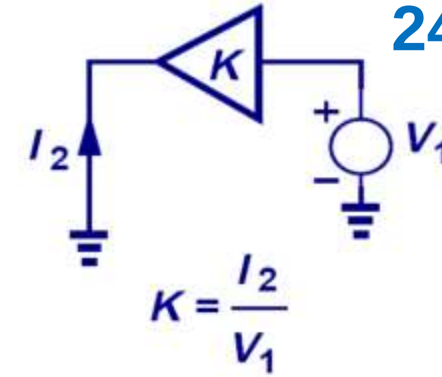
$$\frac{V_{out}}{I_{in}}\Big|_{open} = \frac{R_F R_D}{R_F + 1/g_{m1}}[-g_{m2}(R_F \parallel R_M)]$$

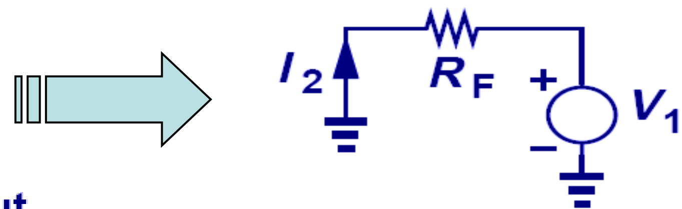
$$R_{in,open} = \frac{1}{g_{m1}} \parallel R_F$$

$$R_{out,open} = R_F \parallel R_M$$

Feedback Factor Example VIII







$$K = -1/R_F$$

$$(V_{out}/I_{in})|_{closed} = (V_{out}/I_{in})|_{open} \,/[1 + K(V_{out}/I_{in})|_{open}]$$

$$R_{in,closed} = R_{in,open} \,/[1 + K(V_{out}/I_{in})|_{open}]$$

$$R_{out,closed} = R_{out,open} \,/[1 + K(V_{out}/I_{in})|_{open}]$$

11.5.4. The Feedback Current Amplifier

电流并联负反馈（感知电流，返回电流）

理想的“电流并联负反馈”

① 正向放大电路（A circuit）具有输入电阻 R_i，输出电阻 R_o，开环增益 A

②反馈网络（β circuit）具有反馈因子 β

$$I_f = \beta I_o$$

③闭环增益：

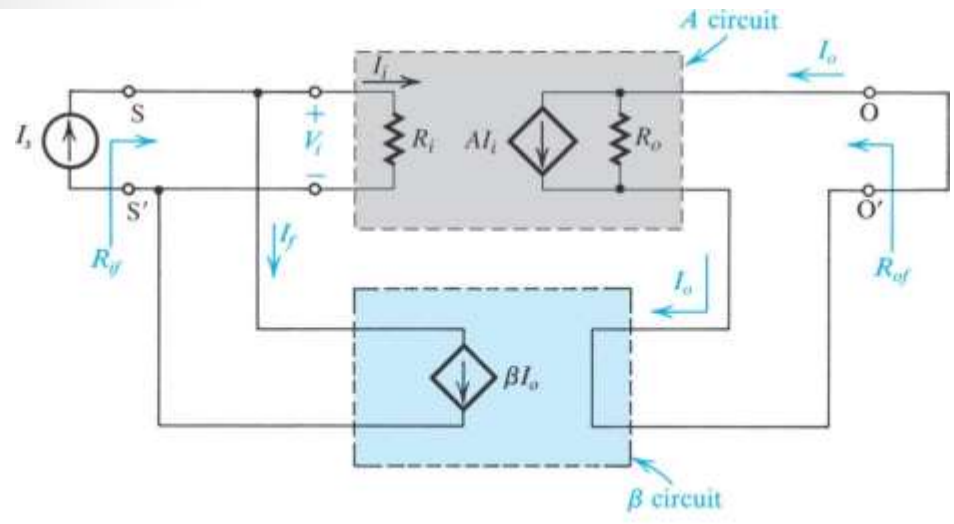
$$A_f \equiv \frac{I_o}{I_s} = \frac{A}{1 + A\beta}$$

④闭环输入电阻降低：

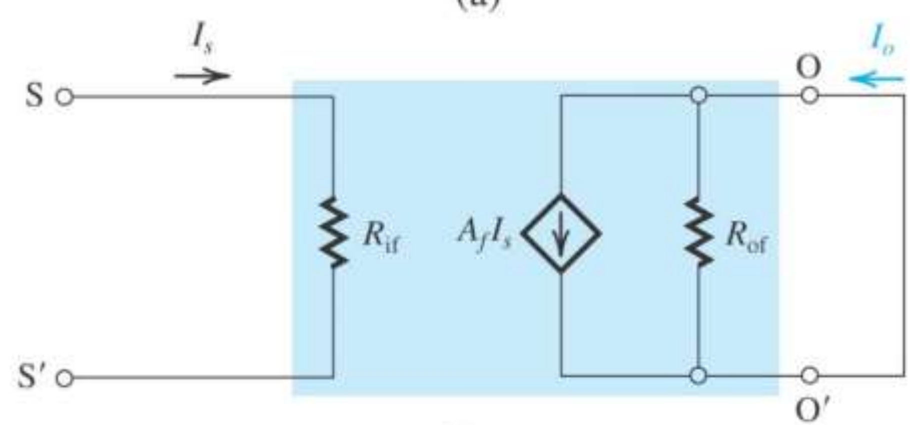
$$R_{if} = \frac{R_i}{1 + A\beta}$$

⑤闭环输出电阻增加

$$R_{of} = (1 + A\beta)R_o$$



(a)



(b)

- 对于一个实际的负反馈电路，我们的目标：finding A & β；

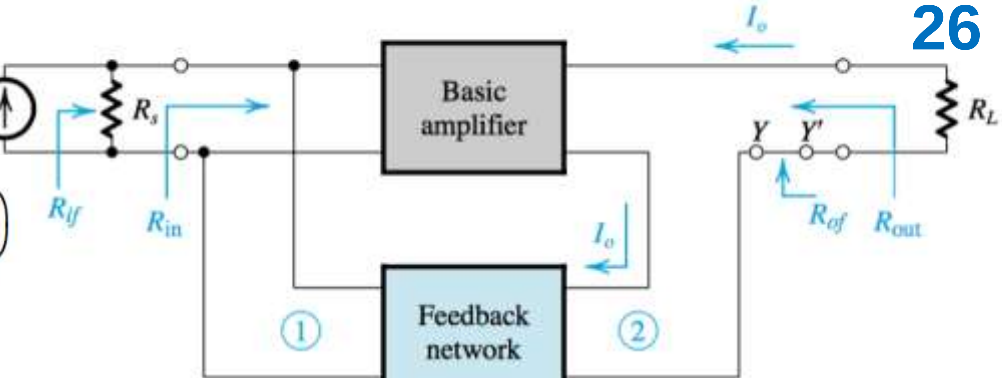
- 求反馈网络①端口向右看的等效电阻R_{11}（此时②端口串联到主电路，destroy串联，故②端口开路）；

- 求反馈网络②端口向左看的等效电路R_{22}，同理，①端口短路；

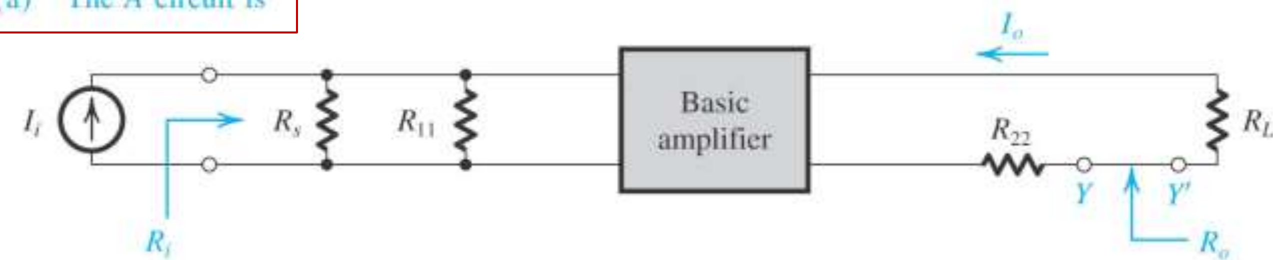
- 将R_{11}和R_{22}包含进主电路，形成 A 电路，分别计算A及β

$$R_{in} = 1\Big/\left(\frac{1}{R_{if}} - \frac{1}{R_s}\right)$$

$$R_{out} = R_{of} - R_L$$

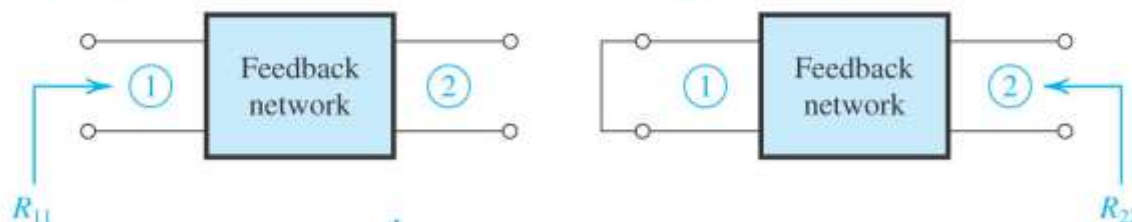


(a) The A circuit is



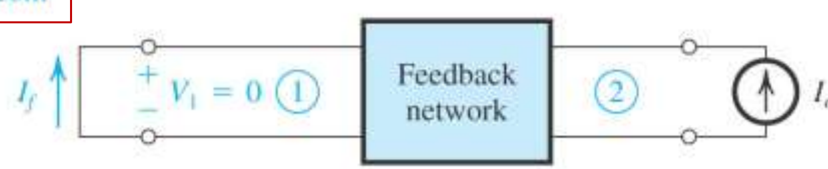
where R_{11} is obtained from

and R_{22} is obtained from



and the gain A is defined as $A \equiv \frac{I_o}{I_i}$

(b) β is obtained from

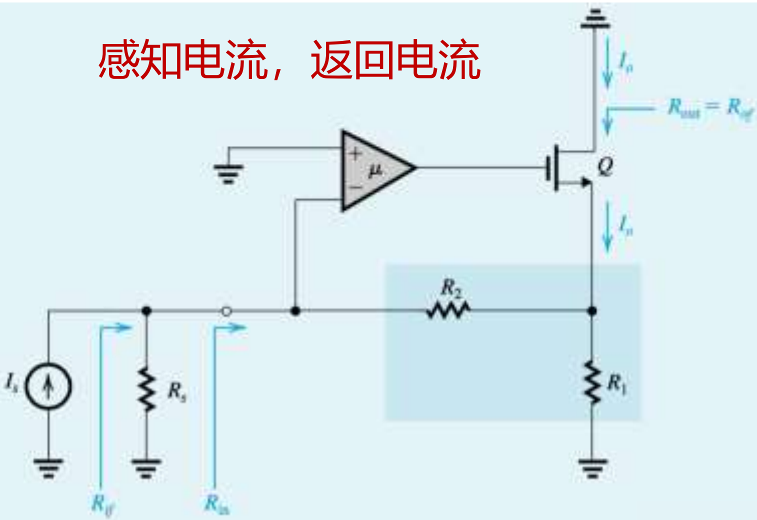


$$\beta \equiv \left.\frac{I_f}{I_o}\right|_{V_1=0}$$

Example 11.10

Figure 11.27 shows a feedback current amplifier formed by cascading an inverting voltage amplifier μ with a MOSFET Q. The output current I_o is the drain current of Q. The feedback network, consisting of resistors R_1 and R_2, senses an exactly equal current, namely, the source current of Q, and provides a feedback current signal that is mixed with I_s at the input node. Note that the bias arrangement is *not* shown.

感知电流，返回电流



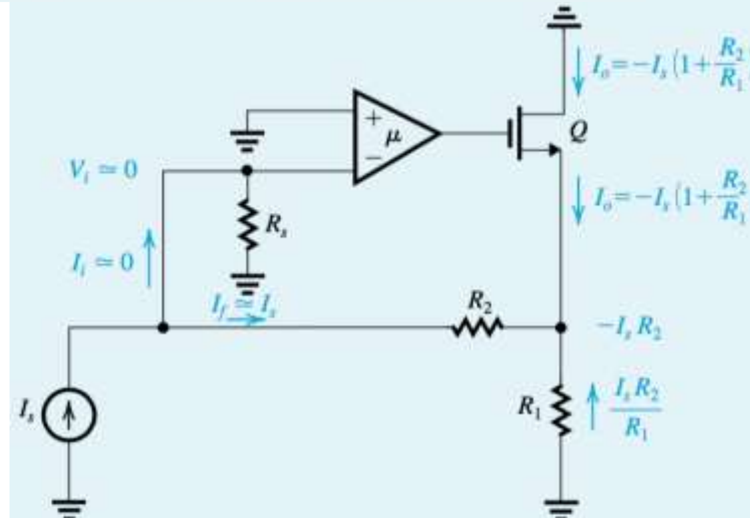
(a)

③

$$R_{if} = R_i/(1 + A\beta)$$

$$R_{of} = R_o(1 + A\beta)$$

$$A_f \simeq -\left(1 + \frac{R_2}{R_1}\right)$$

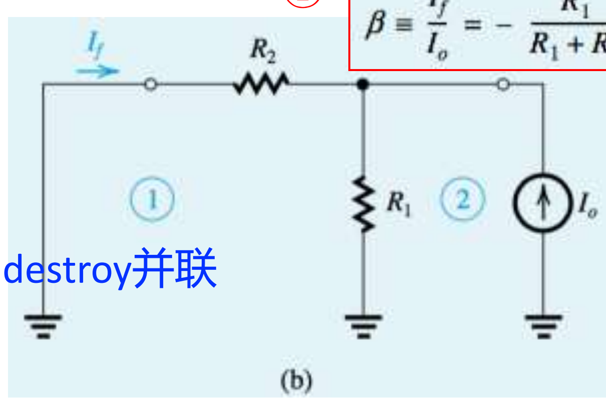


②

$$R_i = R_s \| R_{id} \| (R_1 + R_2) \qquad R_o = r_{o2} + (R_1 \| R_2) + (g_m r_{o2})(R_1 \| R_2)$$

①

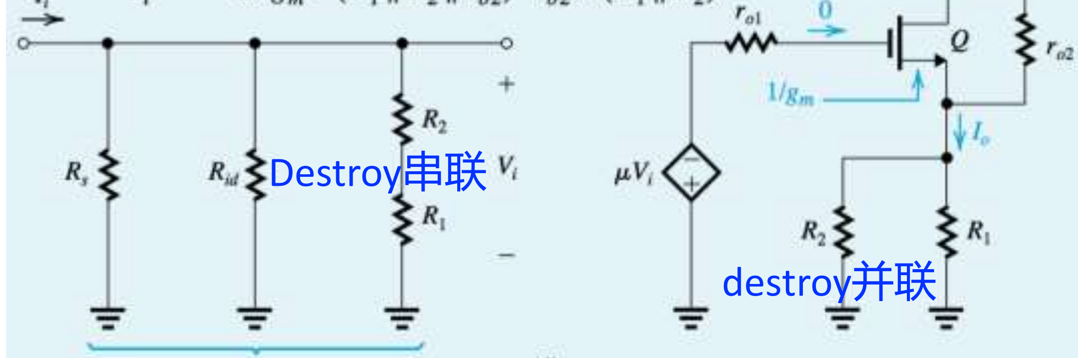
$$\boxed{\beta \equiv \frac{I_f}{I_o} = -\frac{R_1}{R_1 + R_2}}$$



destroy并联

(b)

$$A \equiv \frac{I_o}{I_i} = -\mu \frac{R_i}{1/g_m + (R_1 \| R_2 \| r_{o2})} \frac{r_{o2}}{r_{o2} + (R_1 \| R_2)}$$

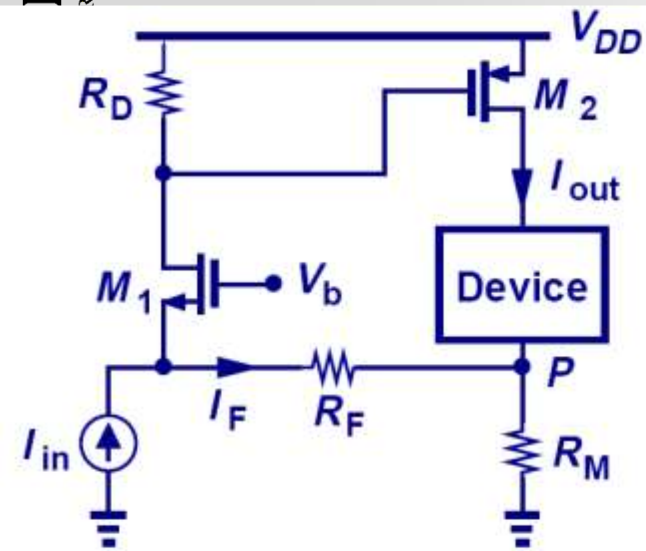


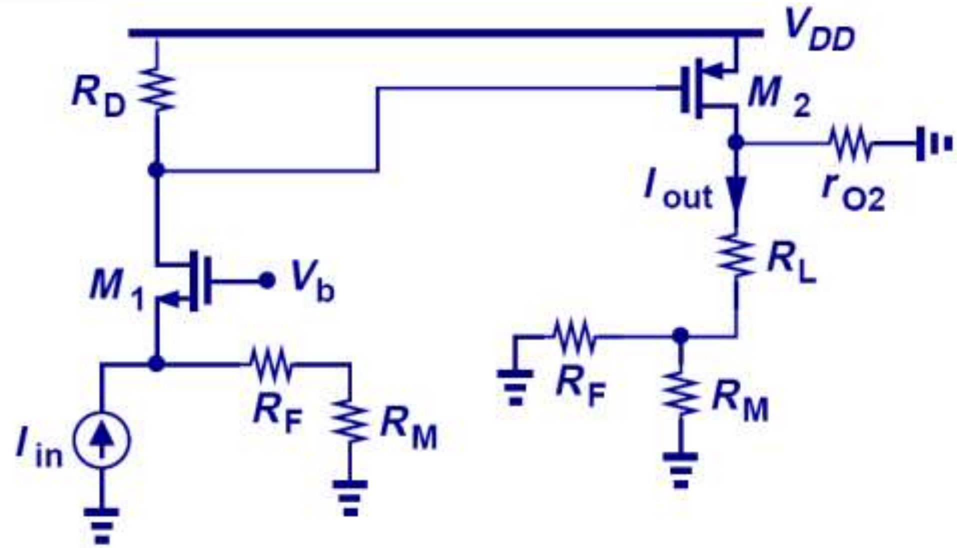
Destroy串联

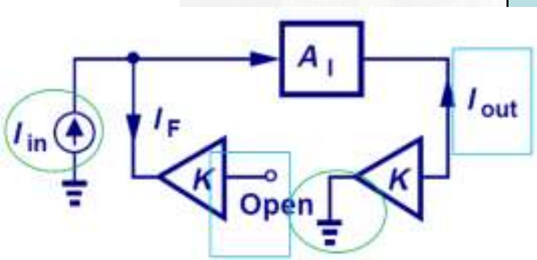
destroy并联

(d)

Breaking the Loop Example VII







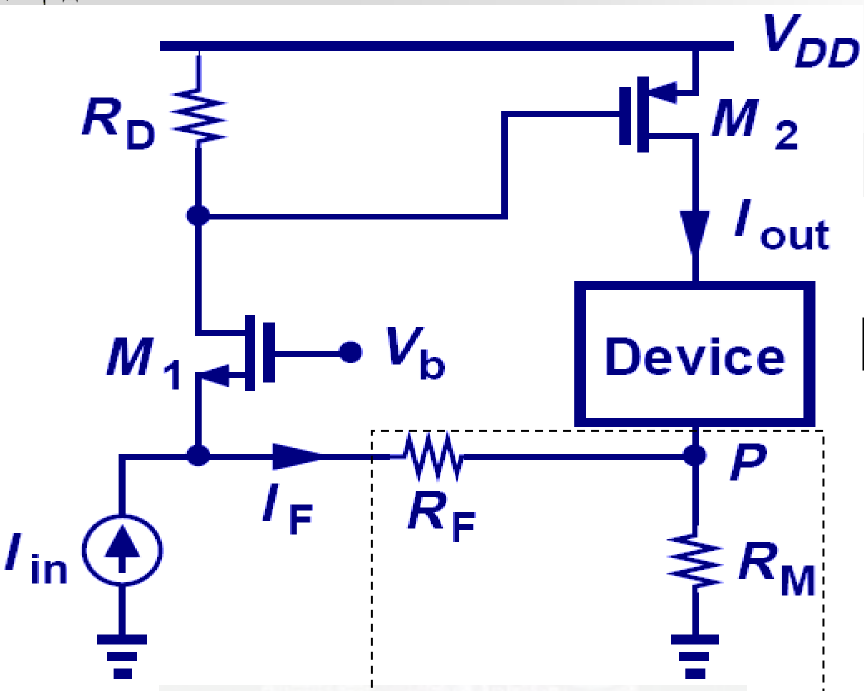
(c)

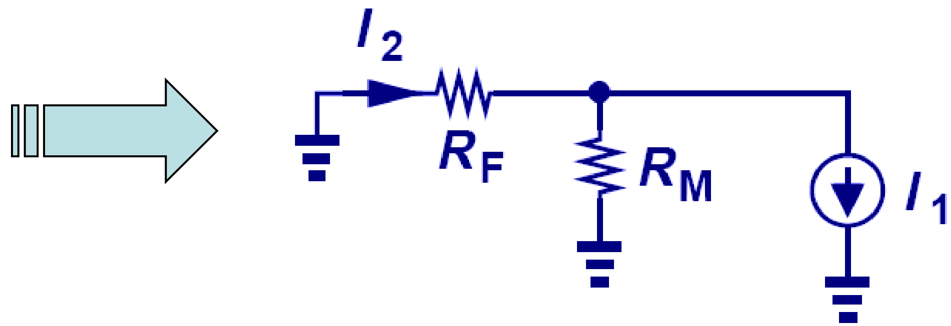
$$A_{I,open} = \frac{(R_F + R_M)R_D}{R_F + R_M + \frac{1}{g_{m1}}} \cdot \frac{-g_{m2}r_{O2}}{r_{O2} + R_L + R_M \parallel R_F}$$

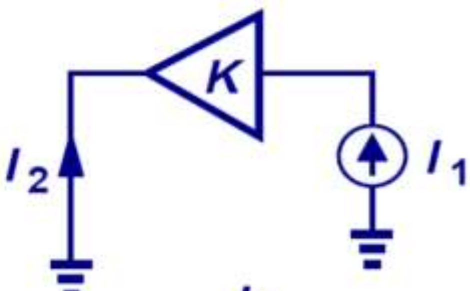
$$R_{in,open} = \frac{1}{g_{m1}} \parallel (R_F + R_M)$$

$$R_{out,open} = r_{O2} + R_F \parallel R_M$$

Feedback Factor Example VII







$$K = \frac{I_2}{I_1}$$

$$K = -R_M/(R_F + R_M)$$

$$A_{I,closed} = A_{I,open}/(1 + KA_{I,open})$$

$$R_{in,closed} = R_{in,open}/(1 + KA_{I,open})$$

$$R_{out,closed} = R_{out,open}(1 + KA_{I,open})$$

四种负反馈组态的总结

Table 11.2 Summary of Relationships for the Four Feedback-Amplifier Topologies

Feedback Amplifier	Feedback Topology	x_i	x_o	x_f	x_s	A	β	A_f	Source Form	Loading of Feedback Network Is Obtained: At Input	Loading of Feedback Network Is Obtained: At Output	To Find β, Apply to Port 2 of Feedback Network	R_{if}	R_{of}	Refer to Figs.
Voltage	Series–shunt	V_i	V_o	V_f	V_s	$\frac{V_o}{V_i}$	$\frac{V_f}{V_o}$	$\frac{V_o}{V_s}$	Thévenin	By short-circuiting port 2 of feedback network	By open-circuiting port 1 of feedback network	a voltage, and find the open-circuit voltage at port 1	$R_i(1+A\beta)$	$\frac{R_o}{1+A\beta}$	11.12 11.14
Current	Shunt–series	I_i	I_o	I_f	I_s	$\frac{I_o}{I_i}$	$\frac{I_f}{I_o}$	$\frac{I_o}{I_s}$	Norton	By open-circuiting port 2 of feedback network	By short-circuiting port 1 of feedback network	a current, and find the short-circuit current at port 1	$\frac{R_i}{1+A\beta}$	$R_o(1+A\beta)$	11.25 11.26
Transconductance	Series–series	V_i	I_o	V_f	V_s	$\frac{I_o}{V_i}$	$\frac{V_f}{I_o}$	$\frac{I_o}{V_s}$	Thévenin	By open-circuiting port 2 of feedback network	By open-circuiting port 1 of feedback network	a current, and find the open-circuit voltage at port 1	$R_i(1+A\beta)$	$R_o(1+A\beta)$	11.18 11.19
Transresistance	Shunt–shunt	I_i	V_o	I_f	I_s	$\frac{V_o}{I_i}$	$\frac{I_f}{V_o}$	$\frac{V_o}{I_s}$	Norton	By short-circuiting port 2 of feedback network	By short-circuiting port 1 of feedback network	a voltage, and find the short-circuit current at port 1	$\frac{R_i}{1+A\beta}$	$\frac{R_o}{1+A\beta}$	11.22 11.23

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环路极性法的步骤为：

1）找到反馈环路。

2）在反馈环路中任意确定一个节点 A。

3）在节点 A 处假设存在一个正的变化量，用⊕表示。

4）沿着反馈环路，让这个变化量依次行进，每过一个关键节点，对变化量方向进行判断并标注，用⊕表示正变化量，用⊖表示负变化量，用⓪表示没有变化量。

5）等这个行进过程再次回到 A 点时，如果变化量仍是⊕，则表明反馈的作用是赞成初始的变化，起到了推波助澜的作用，属于正反馈。如果变化量为⊖，则表明反馈的作用是反对初始的变化，起到了唱反调的作用，属于负反馈。如果变化量为⓪，则表明反馈环路被打断，不存在反馈。

极性传递的典型情况

图 Section59-3 给出了一些常见的极性传递情况，用于上述第 4 步中变化量行进之中。常见的电阻、电容、二极管等无源元件，一般只能实现同相传递，但在敏感频率处，需要另议。运放和晶体管可以同相传递，也可以反相传递，在晶体管中，牢记：共射极电路的输入是基极，输出是集电极，两者反相，共集电极电流的输入是基极，输出是发射极，两者是同相的，共基极电路的输入是发射极，输出是集电极，两者是同相的。

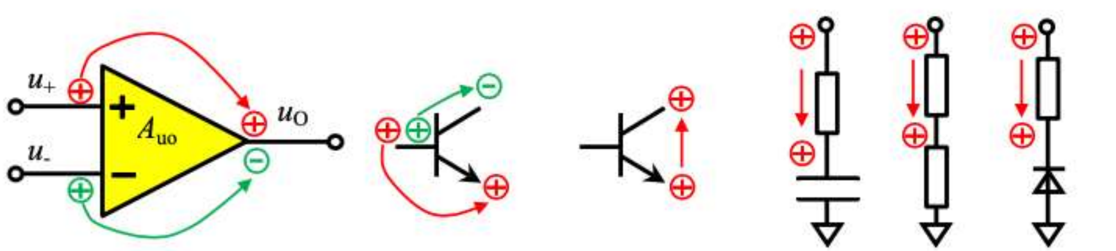


图 Section59-3 一些常见的极性传递情况

放大器中引入负反馈的一般原则（中文教材p292）

引入负反馈可以改善放大电路多方面的性能，而且反馈组态不同，所产生的影响也各不相同。因此，在设计放大电路时，应根据需要和目的，引入合适的反馈，这里提供部分一般原则。

首先要保证引入的是负反馈

（1）为了稳定静态工作点，应引入直流负反馈；为了改善电路的动态性能，应引入交流负反馈。

（2）根据信号源的性质决定引入串联负反馈或并联负反馈。当信号源为恒压源或内阻较小的电压源时，为增大放大电路的输入电阻，以减小信号源的输出电流和内阻上的压降，应引入串联负反馈。当信号源为恒流源或内阻很大的电压源时，为减小放大电路的输入电阻，使电路获得更大的输入电流，应引入并联负反馈。

（3）根据负载对放大电路输出量的要求，即负载对其信号源的要求，决定引入电压负反馈或电流负反馈。当负载需要稳定的电压信号时，应引入电压负反馈；当负载需要稳定的电流信号时，应引入电流负反馈。

（4）根据表 6.3.1 所示的四种组态反馈电路的功能，在需要进行信号变换时，选择合适的组态。例如，若将电流信号转换成电压信号，则应引入电压并联负反馈；若将电压信号转换成电流信号，则应引入电流串联负反馈，等等。

【例 6.5.1】 电路如图 6.5.8 所示，为了达到下列目的，分别说明应引入哪种组态的负反馈以及电路如何连接。

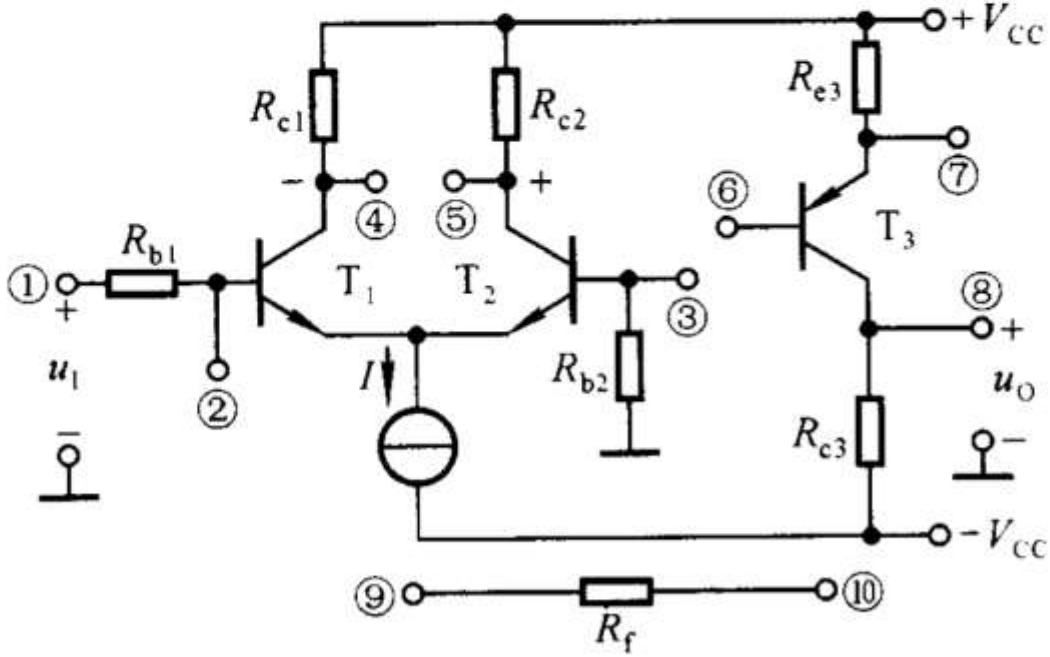


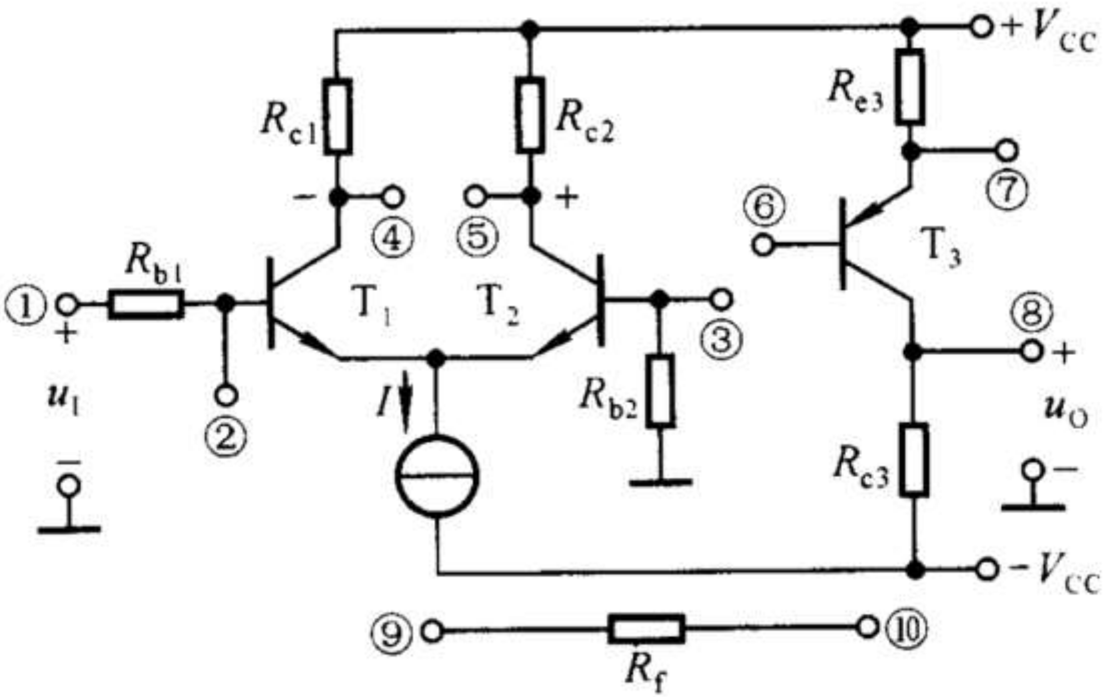
图 6.5.8 例 6.5.1 电路图

(1) 减小放大电路从信号源索取的电流并增强带负载能力；

(2) 将输入电流 i_I 转换成与之成稳定线性关系的输出电流 i_O；

(3) 将输入电流 i_I 转换成稳定的输出电压 u_O。

解：若 u_I 瞬时极性对地为"+"，则 T_1 管集电极电位为"-"，T_2 管集电



极电位为“+”，如图中所标注；而若要 T_3 管的发射极电位为“+”，集电极电位为“-”，则需将其基极接 T_2 管集电极，否则需将其基极接 T_1 管集电极。

(1) 电路需要增大输入电阻并减小输出电阻，故应引入电压串联负反馈。

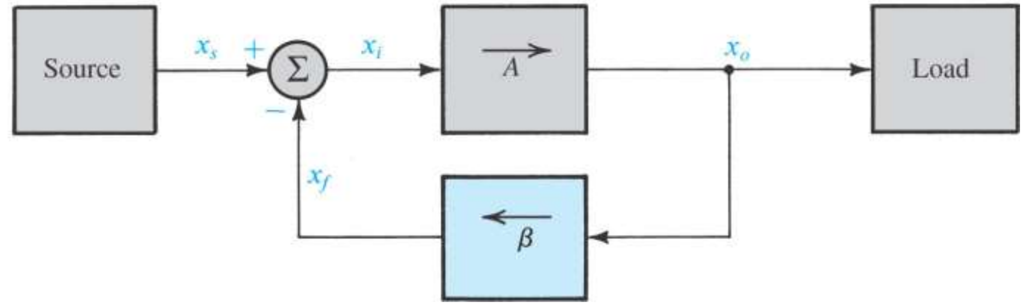
反馈信号从输出电压采样，故将⑧与⑩相连接；反馈量应为电压量，故将③与⑨相连接；这样，u_O 作用于 R_f 和 R_{b2} 回路，在 R_{b2} 上得到反馈电压 u_F。为了保证电路引入的为负反馈，当 u_I 对地为“+”时，u_F 应为上“+”下“-”，即⑧的电位为“+”，因此应将④与⑥连接起来。

结论：电路中应将④与⑥、③与⑨、⑧与⑩分别连接起来。

10.10 The Stability Problem 稳定性问题

- In a feedback amplifier, the **open loop gain (*A*)** is generally a function of frequency.
- Therefore, it should be called **open-loop transfer function A(*s*).** 同理，
  - β → **feedback transfer function β(s)**
  - Close loop gain A_f → **Close loop transfer function $A_f(s)$**
- One big question is: What happens to gain at higher frequencies?
  - This has huge implications on stability of the amplifier.

10.4.1. The Ideal Case

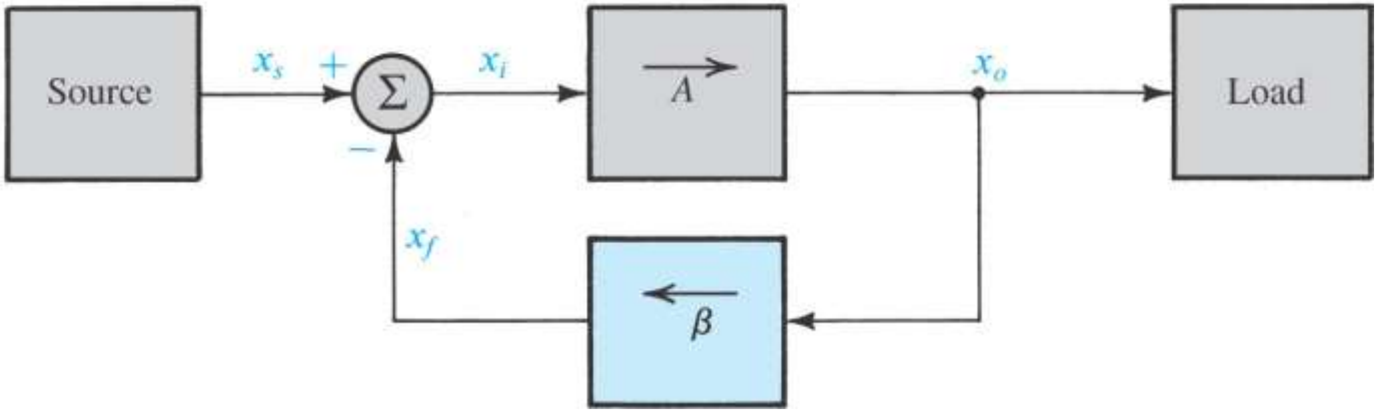


(10.81) closed-loop gain t-function: $\mathbf{A}_f(s) = \dfrac{\mathbf{A}(s)}{1+\mathbf{A}(s)\boldsymbol{\beta}(s)}$

(10.82) closed-loop gain t-function: $\mathbf{A}_f(j\omega) = \dfrac{\mathbf{A}(j\omega)}{1+\mathbf{A}(j\omega)\boldsymbol{\beta}(j\omega)}$

(10.83) loop-gain: $\mathbf{L}(j\omega) = \mathbf{A}(j\omega)\boldsymbol{\beta}(j\omega) = \underbrace{\left|\mathbf{A}(j\omega)\boldsymbol{\beta}(j\omega)\right|}_{\text{magnitude of gain}} e^{j\overbrace{\boldsymbol{\phi}(\omega)}^{\text{angle}}}$

- Loop gain 随频率的变化决定了负反馈放大电路的稳定性（稳定 OR 振荡）
- When $\phi(\omega)$ becomes 180° → ω_{180}: loop gain 成为一个负的实数；输入减去反馈信号 → 输入加上反馈信号；负反馈→正反馈 (输入xs=0，则输出xo=0)
- If at $\omega = \omega_{180}$ the magnitude of the loop gain is less than unity, 增益大于A，但仍稳定
- if at the frequency ω_{180} the magnitude of the loop gain is equal to unity, 增益∞，振荡，零输入信号也会产生输出：若x_s=0，电路的热噪声产生 $X_i \sin(\omega_{180}t)$.
  $X_f = A(j\omega_{180})\beta(j\omega_{180})X_i = -X_i$ → 输入得以保持

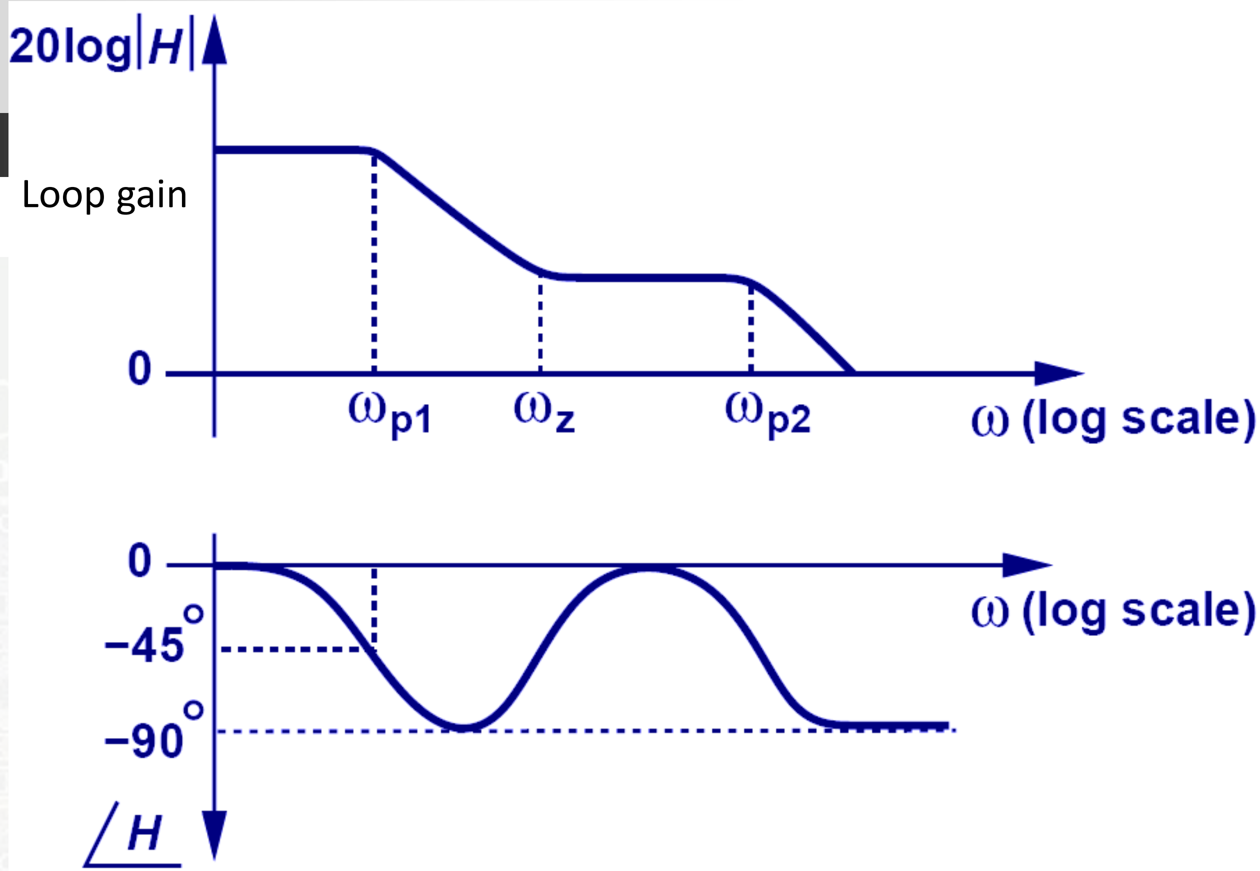


- The question now is: What happens if at ω_{180} the magnitude of the loop gain is greater than unity?

- 产生振荡， x_i处若有一随机噪声，该噪声的幅度会持续放大，直至电路中的非线性效应导致信号幅度达到饱和

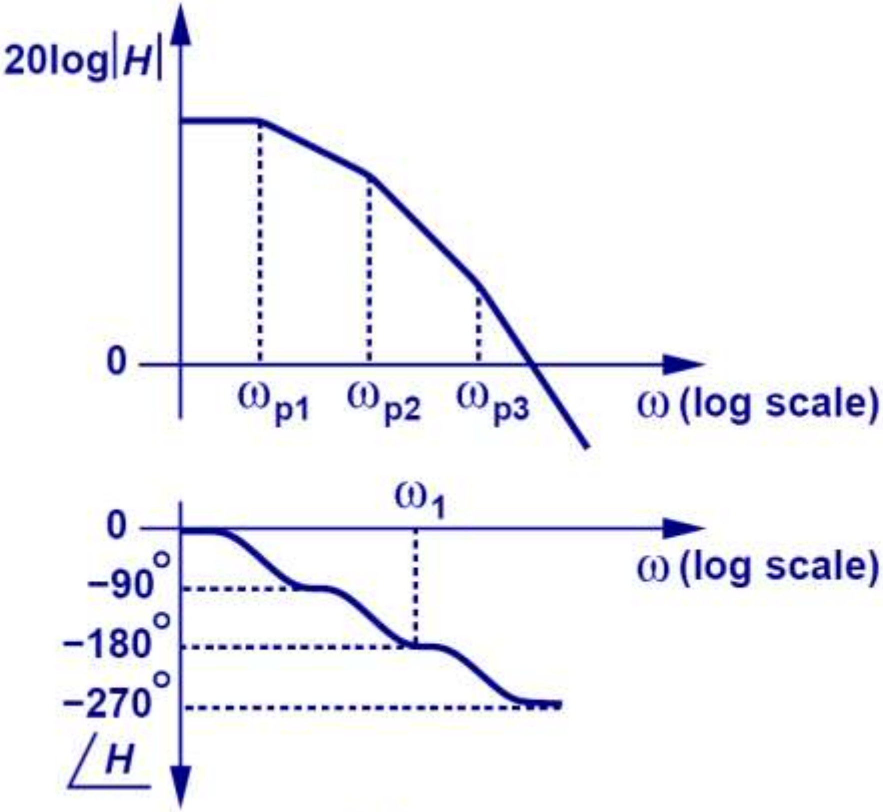
11.9. **Stability Study Using Bode Plots** 使用波特图判断稳定性

Example: Phase Response 相位响应



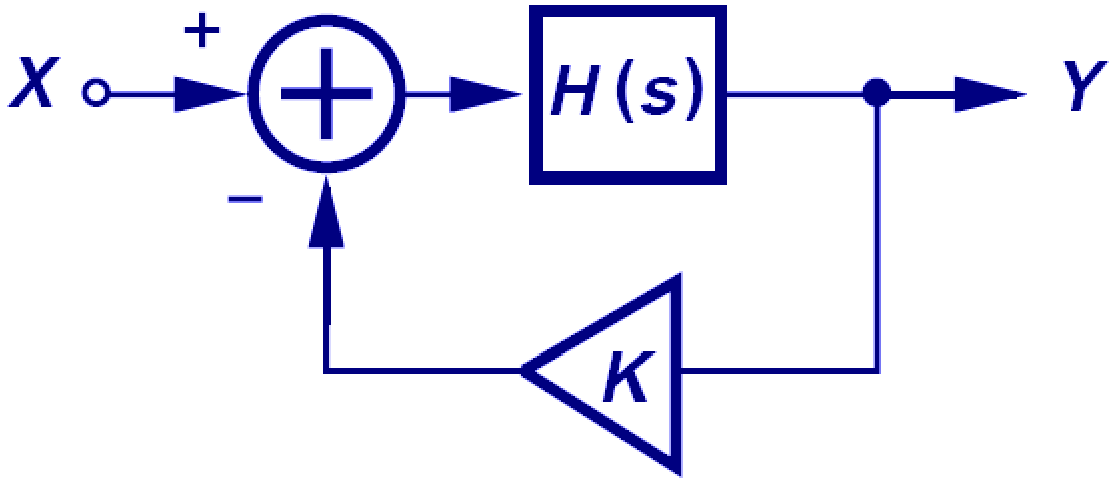
- 每极点相位减小90°，每零点相位增加90°
- 从极点（零点）的十分之一频率处开始相位变化，极点（零点）处相位变化达到-45º（45º），极点（零点）十倍频率处达到-90º（90º）

Example: Three-Pole System三极点系统



- 在一个三极点系统中，某一频率的相位可以达到 -180°（在第二极点和第三极点之间），即，输入信号在这个频率点反转

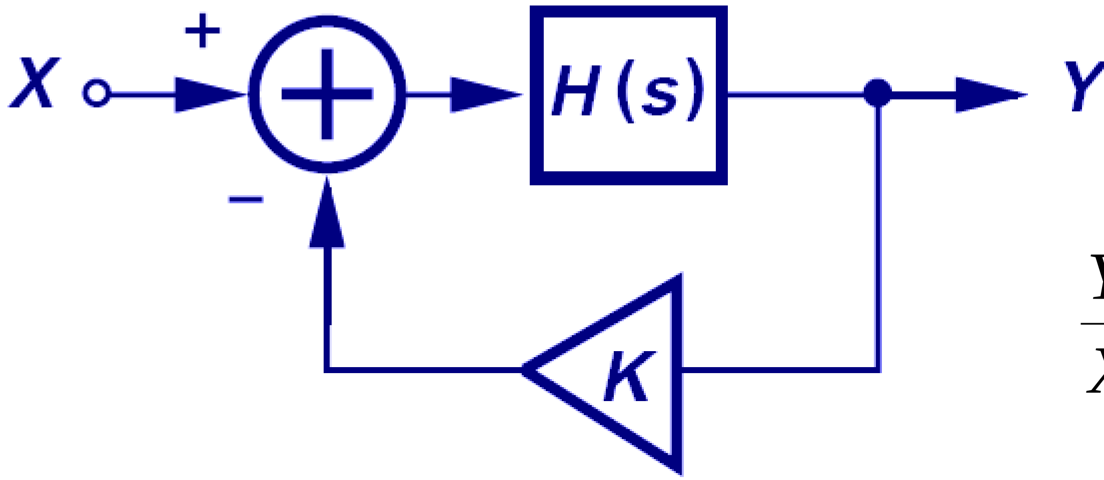
负反馈系统的不稳定性



$$\frac{Y}{X}(s)=\frac{H(s)}{1+KH(s)}$$

- 若在某一频率 ω_1, $KH(j\omega_1)$ 为 -1, 则闭环增益趋于无穷大；也即在频率ω_1 时，非常小的输入信号将有非常大的输出，或者没有输入，也会产生输出，系统变得不稳定。
- 用信号循环的思路理解$KH(j\omega_1)$ <= -1时的不稳定性

"Barkhausen's Criteria" for Oscillation
巴克豪森判据



$$\frac{Y}{X}(s)=\frac{H(s)}{1+KH(s)}$$

$$|KH(j\omega_1)|=1$$

$$\angle KH(j\omega_1)=-180$$

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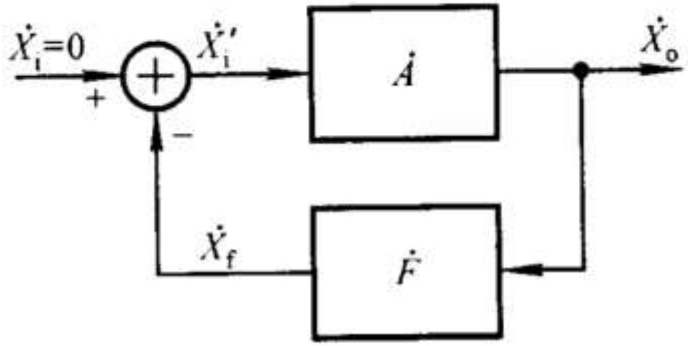

图 6.6.1 负反馈放大电路的自激振荡

SEDRA/SMITH

$$\begin{cases} |\dot{A}\dot{F}| = 1 & (6.6.3a) \\ \varphi_A + \varphi_F = (2n+1)\pi \quad (n\text{ 为整数}) & (6.6.3b) \end{cases}$$

上式称为自激振荡的平衡条件，式(6.6.3a)为幅值平衡条件，式(6.6.3b)为相位平衡条件，简称幅值条件和相位条件。只有同时满足上述两个条件，电路才会产生自激振荡。在起振过程中，$|\dot{X}_o|$有一个从小到大的过程，故起振条件为

$$|\dot{A}\dot{F}| > 1 \tag{6.6.4}$$

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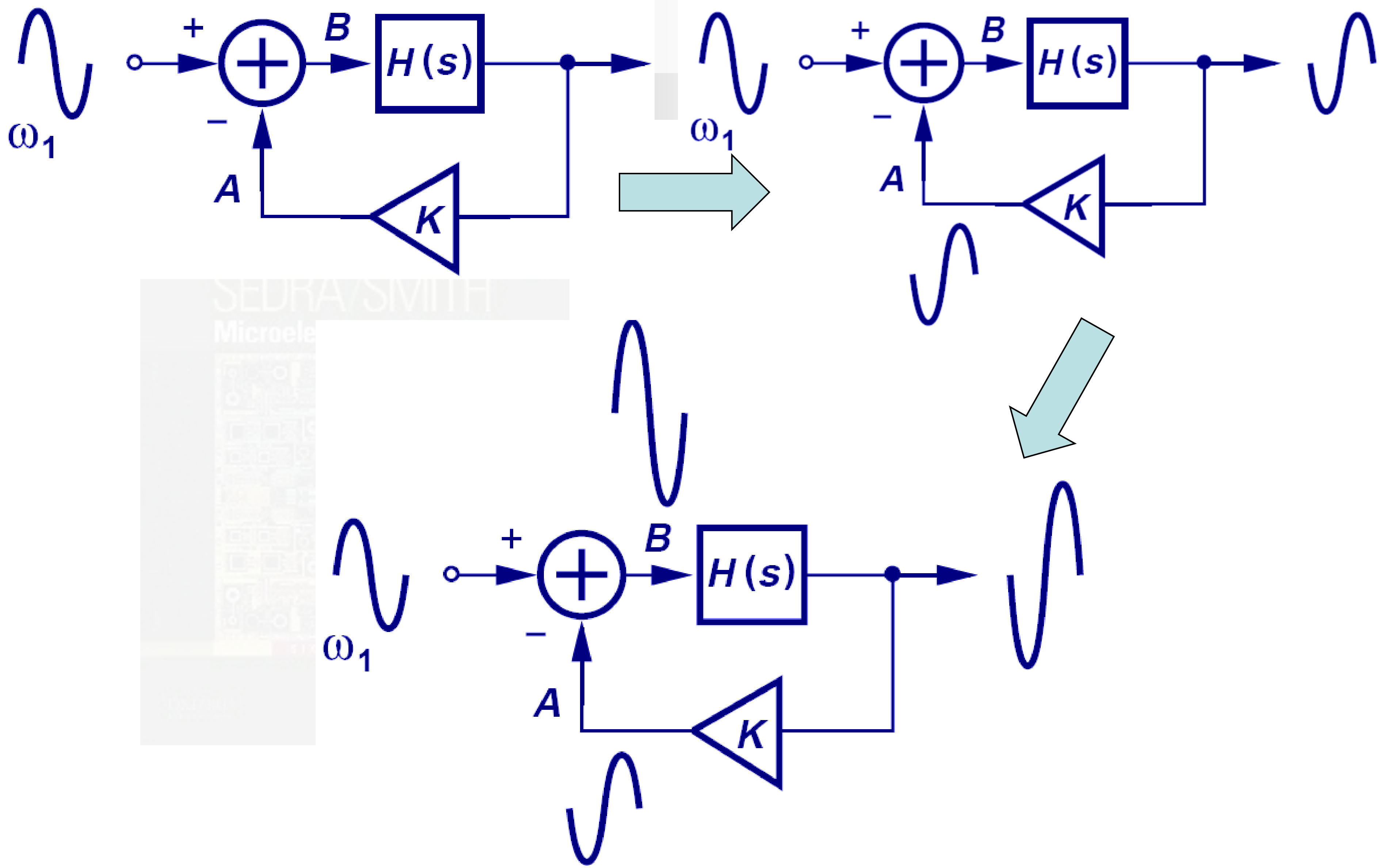
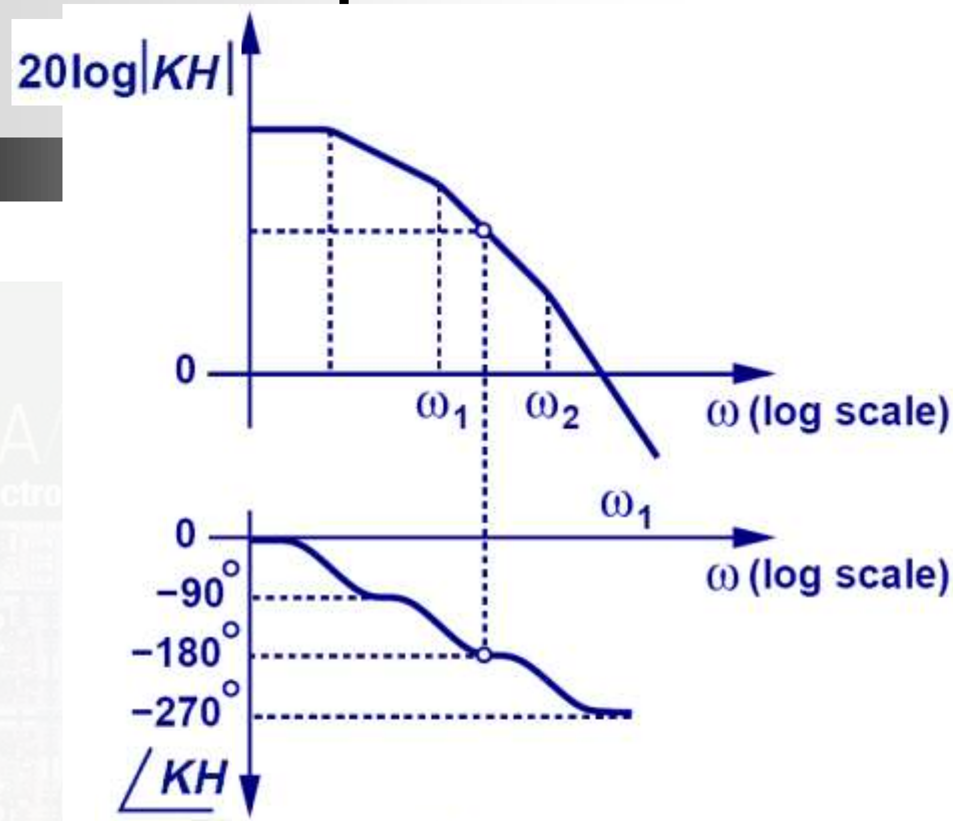
Time Evolution of Instability

此示意图反馈网络不提供极点，相移在主电路实现



Oscillation Example



(c)

- 判断负反馈系统是否会自激振荡的方法：在Aβ的波特图中，先找到 -180º 相位的频率点，再看该点的幅度是否大于1（0dB），大于则会振荡
- 这一系统将会振荡，因为在相位为 -180º 的频率点，Aβ波特图的幅度大于1（0dB）

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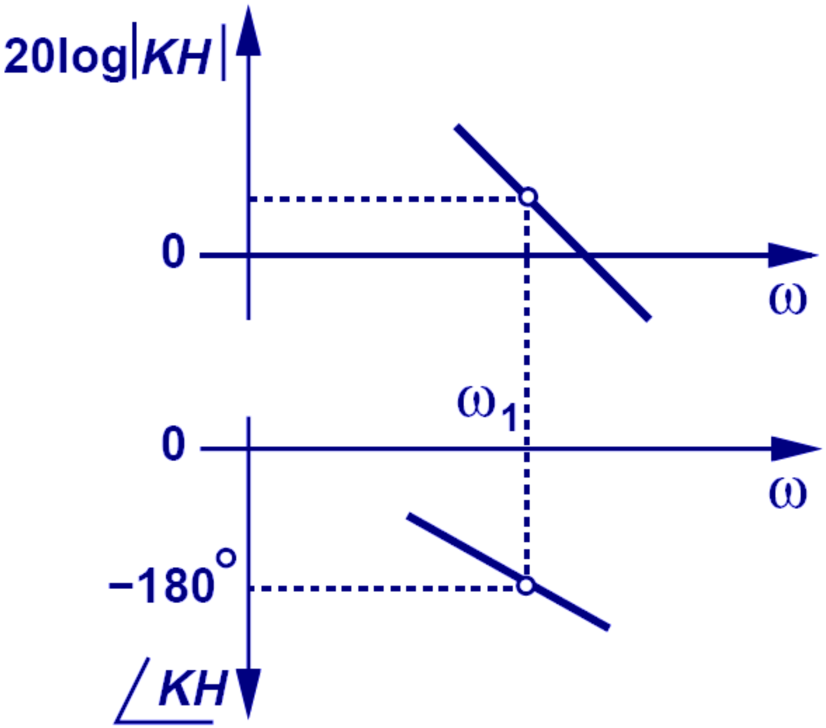
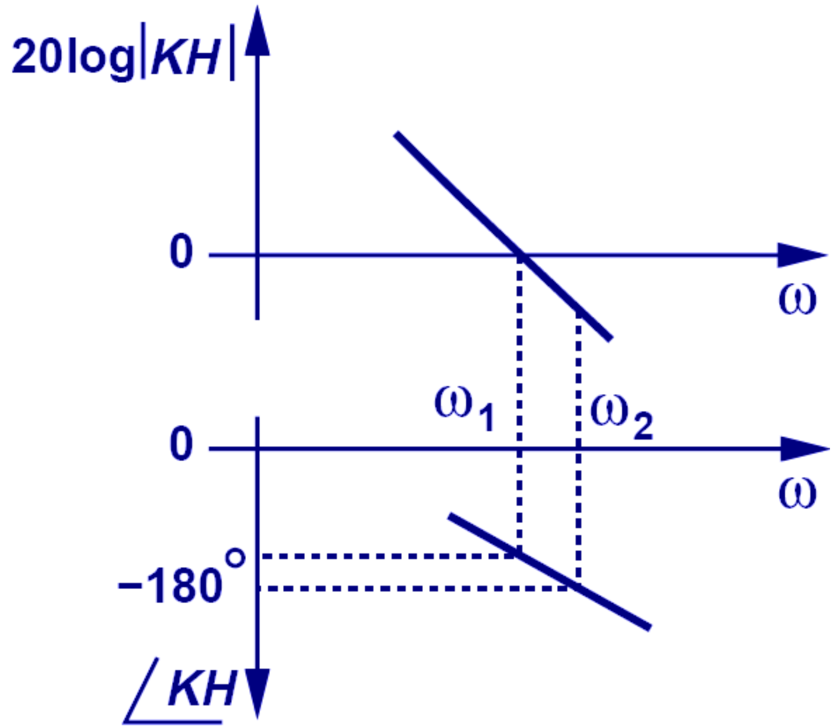
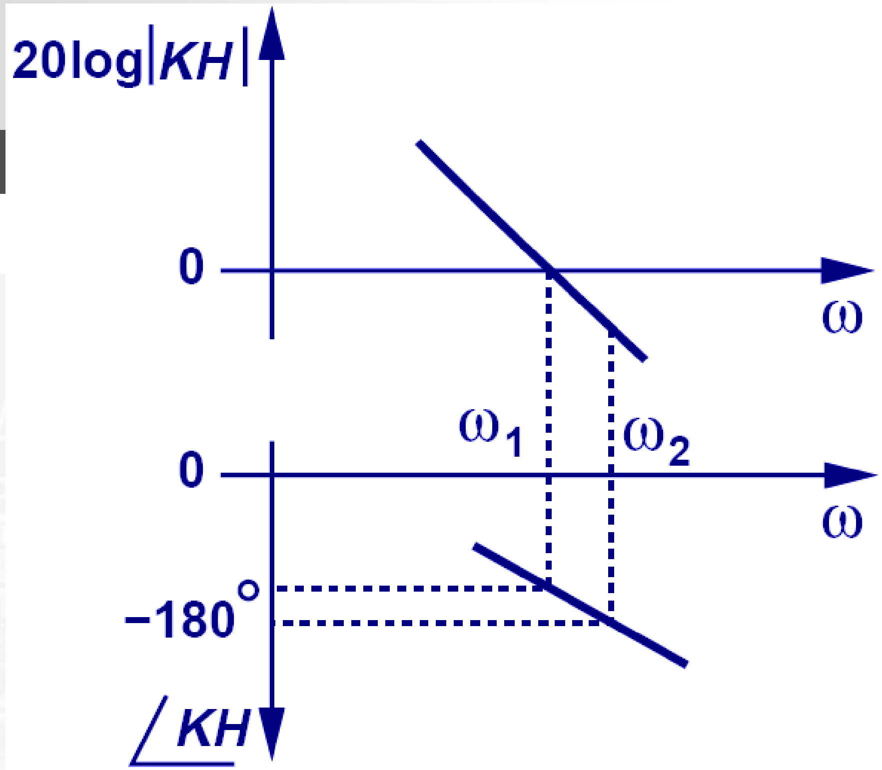
振荡条件





- |KH|=1 and ∠KH=-180º 的频率往往是不一样的；
- 左边的系统当 ∠KH=-180º 时， |KH|>1，所以会振荡；
- 右边的系统当 ∠KH=-180º 时， |KH|<1，所以不会振荡；

稳定性条件



两个角度考虑都可以

①幅度为0dB时，相移没达到180度

②相移180度时，幅度小于0dB

$$\omega_{GX} < \omega_{PX}$$

- ω_{PX}, ("phase crossover"), is the frequency at which ∠KH=-180º.
- ω_{GX}, ("gain crossover"), is the frequency at which |KH|=1.

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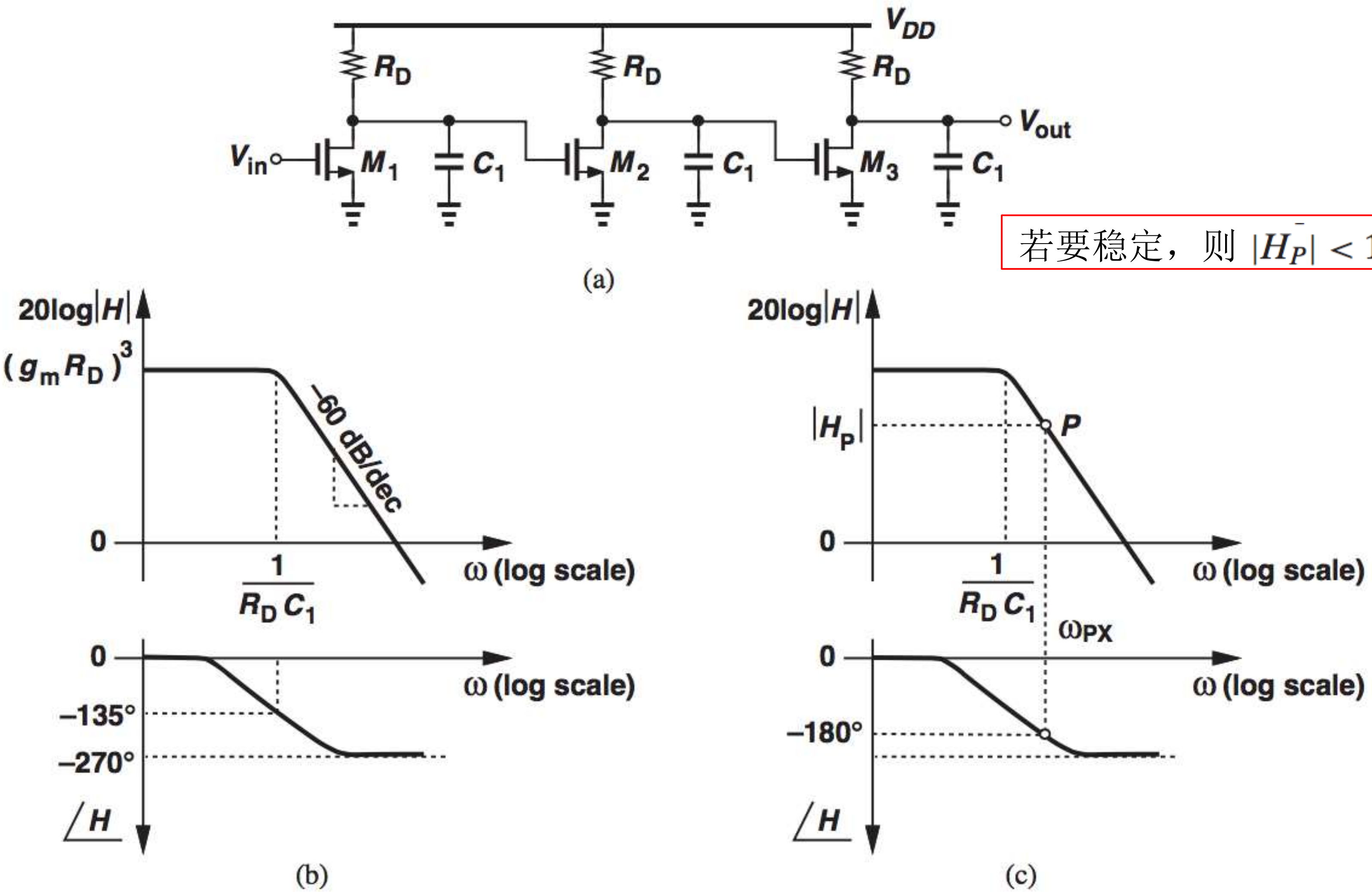
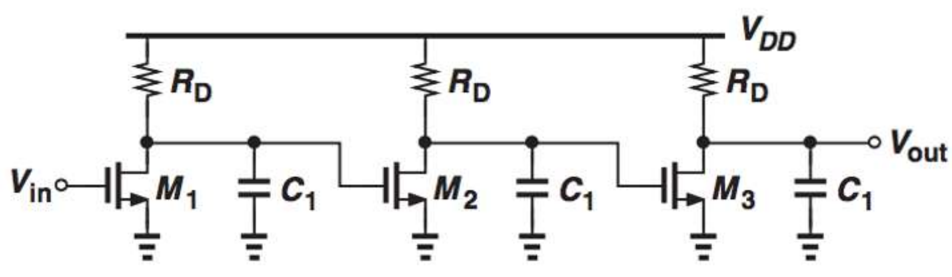
Example 12.38

We wish to apply negative feedback with $K = 1$ around the three-stage amplifier shown in Fig. 12.67(a). Neglecting other capacitances and assuming identical stages, plot the frequency response of the circuit and determine the condition for stability. Assume $\lambda = 0$.



若要稳定，则 $|H_P| < 1$

Figure 12.67



$$H(s) = \frac{(g_m R_D)^3}{\left(1 + \frac{s}{\omega_p}\right)^3}, \quad \text{where } \omega_p = (R_D C_1)^{-1}$$

$$\angle H(j\omega) = -3 \tan^{-1} \frac{\omega}{\omega_p} \Longrightarrow \omega_{PX} = \sqrt{3}\omega_p$$

The magnitude must remain less than unity at this frequency:

$$\frac{(g_m R_D)^3}{\left[\sqrt{1 + \left(\frac{\omega_{PX}}{\omega_p}\right)^2}\right]^3} < 1. \Longrightarrow g_m R_D < 2.$$

If the low-frequency gain of each stage exceeds 2, then a feedback loop around this amplifier with $K = 1$ becomes unstable.

Example 12.39 A common-source stage is placed in a unity-gain feedback loop as shown in Fig. 12.68. Explain why this circuit does not oscillate.

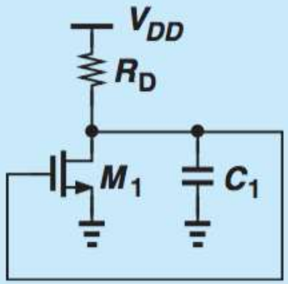


Figure 12.68

Solution Since the circuit contains only one pole, the phase shift cannot reach 180° at any frequency. The circuit is thus stable.

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Example 12.40 Repeat Example 12.38 if the target value of K is 1/2, i.e., the feedback is weaker.

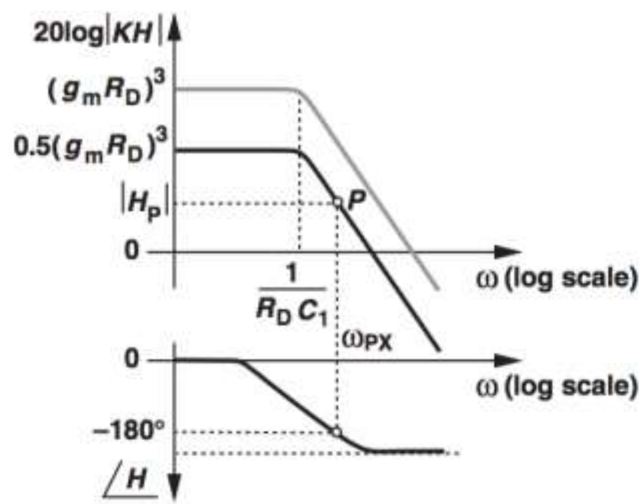
Solution We plot $|KH| = 0.5|H|$ and $\angle KH = \angle H$ as shown in Fig. 12.69(a). Note the $|KH|$ plot is simply shifted down by 6 dB on a logarithmic scale. Starting from the phase crossover frequency, we determine the corresponding point, P, on $|KH|$ and require that $0.5|H_P| < 1$. Recognizing that Eqs. (12.185) and (12.186) still hold, we write

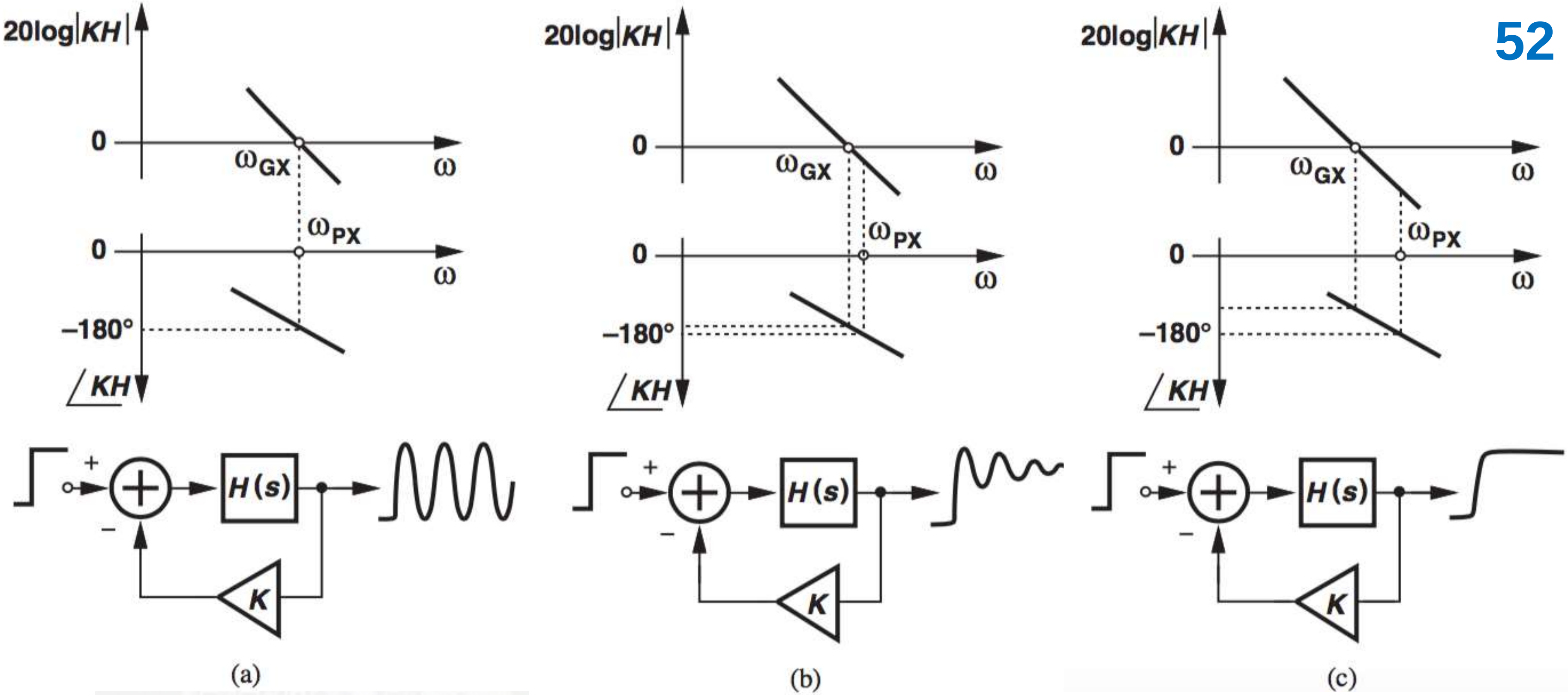
$$\frac{0.5(g_m R_D)^3}{\left[\sqrt{1+\left(\frac{\omega_{PX}}{\omega_p}\right)^2}\right]^3} < 1. \tag{12.189}$$

That is,

$$(g_m R_D)^3 < \frac{2^3}{0.5}. \tag{12.190}$$

Thus, the weaker feedback permits a greater open-loop gain.





Marginally Stable ***Stable***

Figure 12.70 Systems with (a) coincident gain and phase crossovers, (b) gain crossover slightly below phase crossover, (c) gain crossover well below phase crossover.

$$\boxed{\text{Phase Margin} = \angle H(\omega_{GX}) + 180^\circ}$$

Phase Margin (PM，相位裕度)， loop gain 为0dB时对应的相位与-180度之间的差值。PM越大，系统越稳定

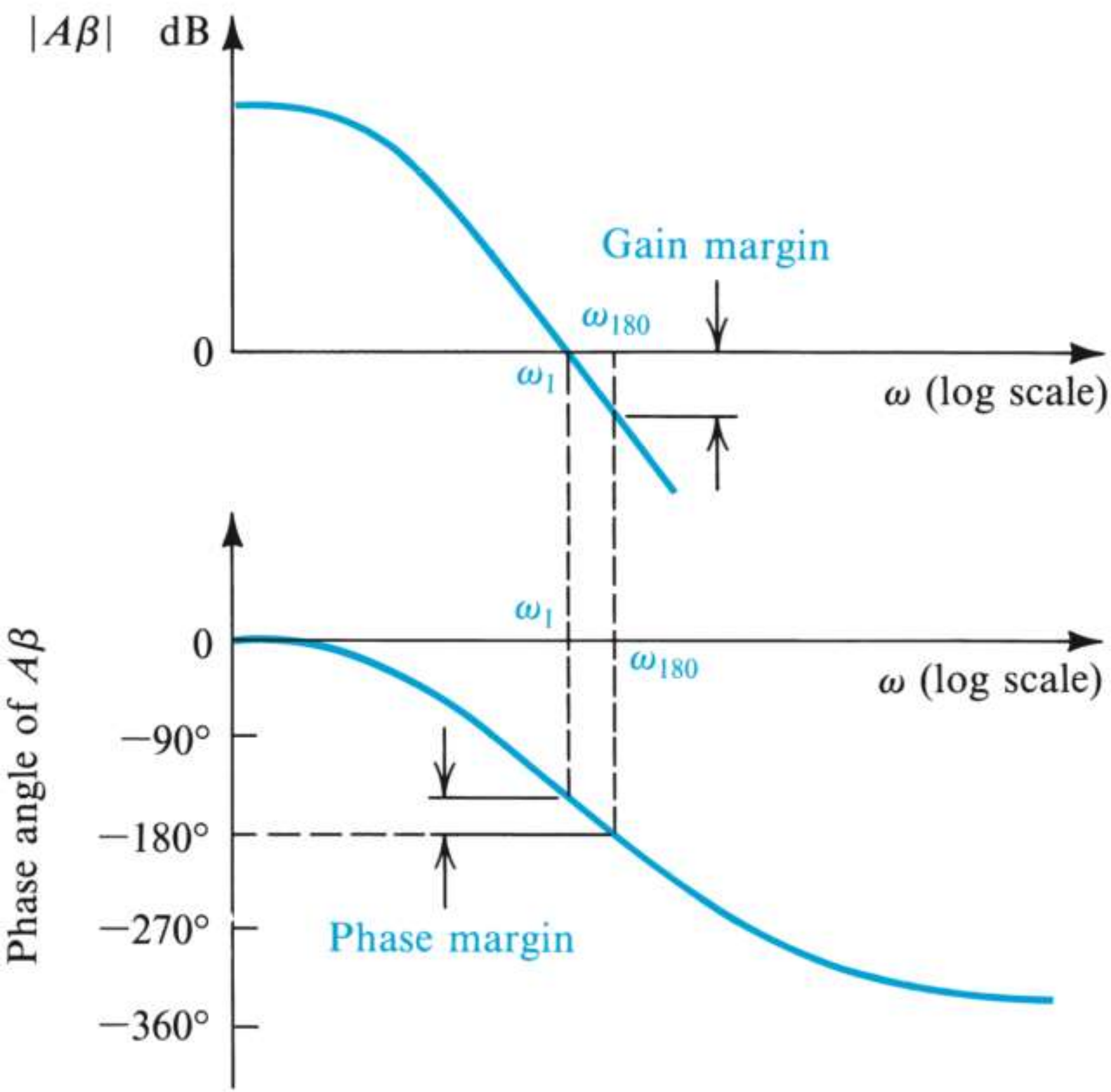


Figure 11.36 Bode plot for the loop gain $A\beta$ illustrating the definitions of the gain and phase margins.

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Example 12.41

Figure 12.71 plots the frequency response of a multipole amplifier. The magnitude drops to unity at the second pole frequency. Determine the phase margin of a feedback system employing this amplifier with $K = 1$.

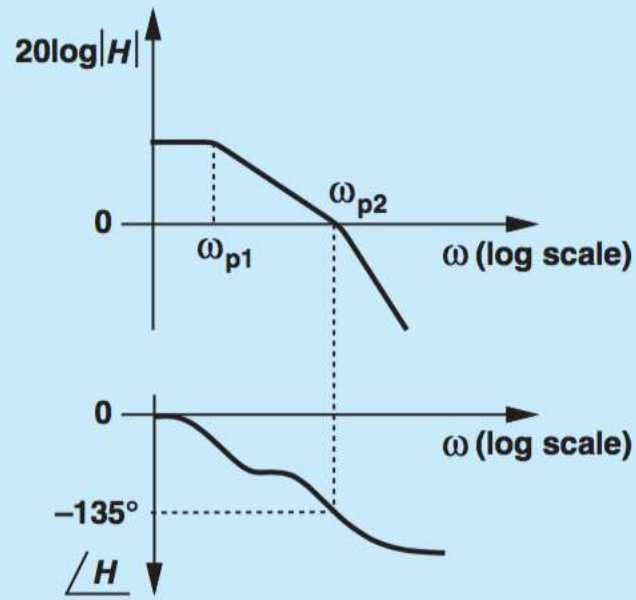


Figure 12.71

Solution The plot suggests that the phase reaches $-135°$ at the second pole frequency (i.e., the poles are far apart). Thus, the phase margin is equal to 45°.

Phase Margin 多少才足够？
①至少45°，也即 Gain Crossover要小于第二个极点
②一个好的设计，往往需要60°的 Phase Margin

频率补偿：滞后补偿

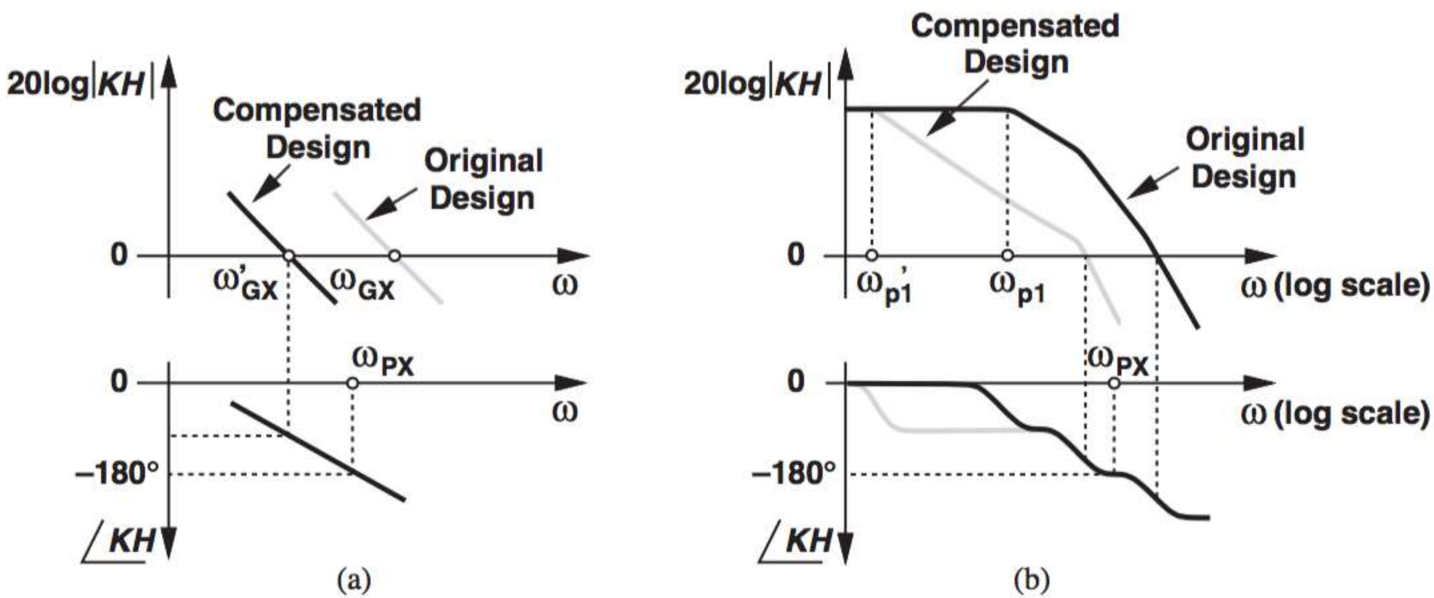


Figure 12.72 (a) Concept of frequency compensation, (b) effect on phase profile.

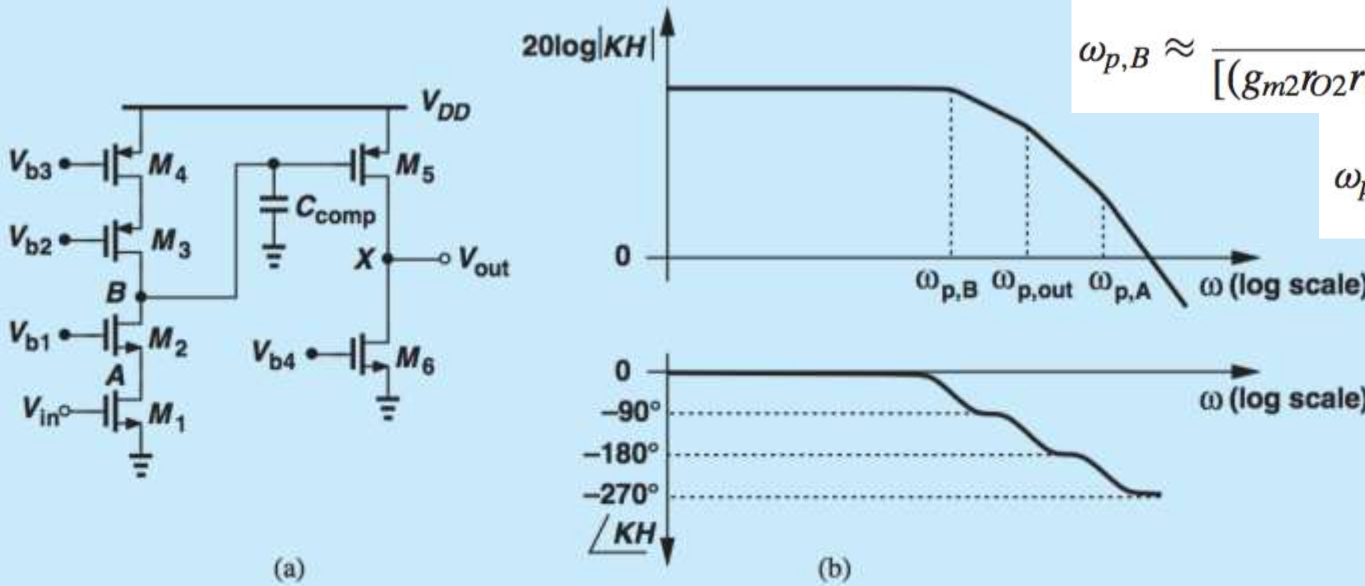
- 提高Phase margin的方法：保持ω_{PX}不变（第二极点的频率不变），减小 ω_{GX}（往左移动，减小第一极点的频率）

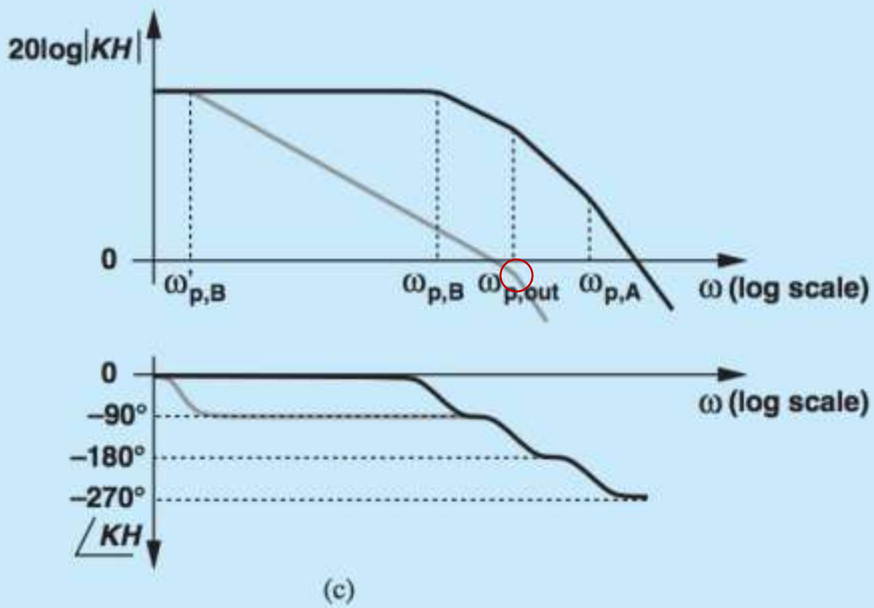
Example 12.42 The amplifier shown in Fig. 12.73(a) employs a cascode stage and a CS stage. Assuming that the pole at node B is dominant, sketch the frequency response and explain how the circuit can be "compensated."

$$\omega_{p,A} \approx \frac{g_{m2}}{C_A}$$

$$\omega_{p,B} \approx \frac{1}{[(g_{m2}r_{O2}r_{O1})||(g_{m3}r_{O3}r_{O4})]C_B}$$

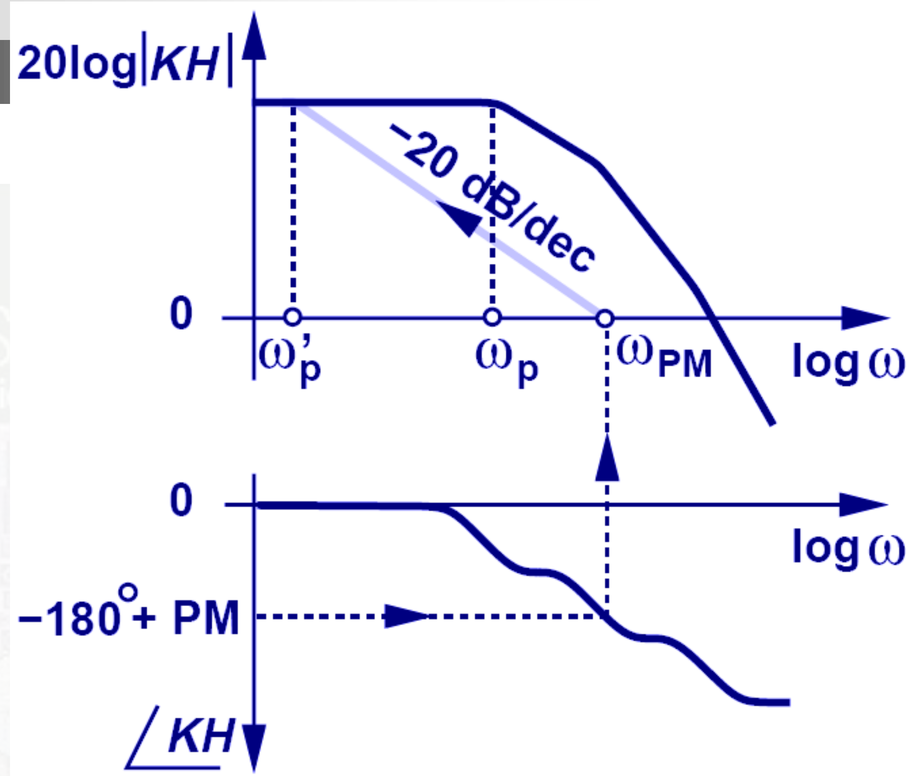
$$\omega_{p,out} = \frac{1}{(r_{O5}||r_{O6})C_{out}}$$





将第一个极点往左移动，使得第二个极点对应的loop gain 减小到0 dB以下（第二个极点对应的相位为-135°）

Frequency Compensation Procedure
频率补偿的步骤



- 1) 根据需要的PM，-180°+PM 将给定新的 ω_{GX}, or ω_{PM}.（如果PM=45°，就是第二极点）
- 2) 在幅频特性图里，经过 ω_{PM}, 作一斜率为-20dB/dec的直线，与原幅频曲线相交，交点对应的频率点即新的主极点位置 ω_p'.

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Example 12.43

A multipole amplifier exhibits the frequency response plotted in Fig. 12.75(a). Assuming the poles are far apart, compensate the amplifier for a phase margin of 45° with $K = 1$.

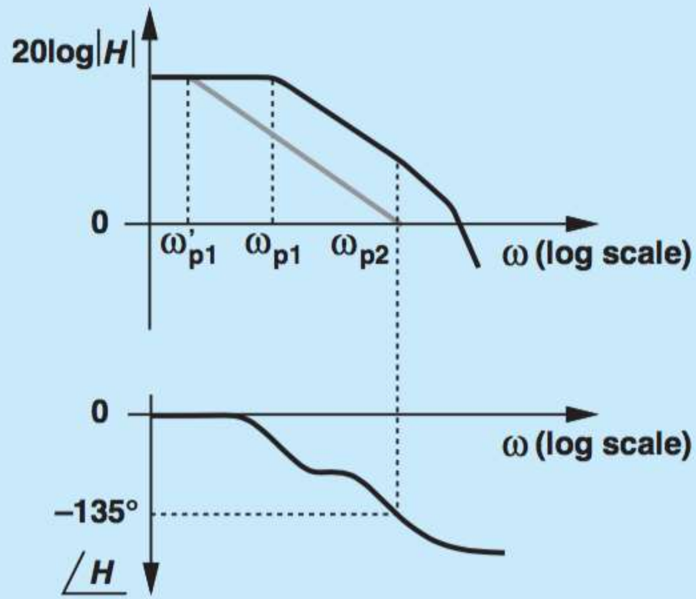

Figure 12.75

思考：在电路上怎么将极点往左移呢?

Solution Since the phase reaches $-135°$ at $\omega = \omega_{p2}$, in this example $\omega_{PM} = \omega_{p2}$. We thus draw a line with a slope of -20 dB/dec from ω_{p2} toward the vertical axis. The dominant pole must therefore be translated to ω'_{p1}. Since this phase margin is generally inadequate, in practice, $\omega_{PM} < \omega_{p2}$.

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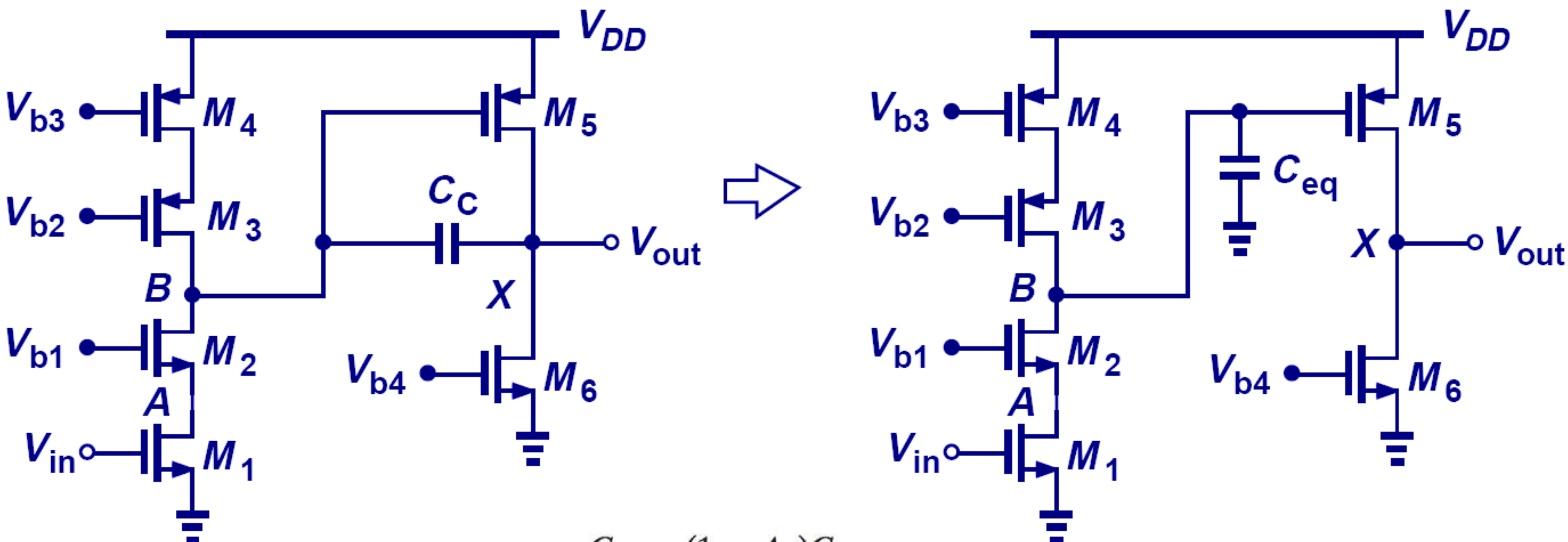
频率补偿：Miller Compensation



$$\begin{aligned} C_{eq} &= (1 - A_v)C_c \\ &= [1 + g_{m5}(r_{O5}||r_{O6})]C_c \end{aligned}$$

- 极点往左移怎么实现？提高RC，Miller补偿提供了增加C的思路
- 在集成电路里，为了减小电容所占用的面积，利用Miller multiplication，可用小电容产生大电容，形成等效的主极点，即**Miller补偿**

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①仅对开环增益 A 画波特图

$$A = \frac{10^5}{(1+jf/10^5)(1+jf/10^6)(1+jf/10^7)}$$

$$\phi = -[\tan^{-1}(f/10^5) + \tan^{-1}(f/10^6) + \tan^{-1}(f/10^7)]$$

②假设β与频率无关，可用水平直线表示1/β，如图中的（a）（b）

$$20\log|A(j\omega)| - 20\log\frac{1}{\beta} = 20\log|A\beta|$$

③两者之差为Aβ的波特图，可判断出（a）是稳定的，而（b）是不稳定的；1/β 最小需要 60 dB，系统才稳定

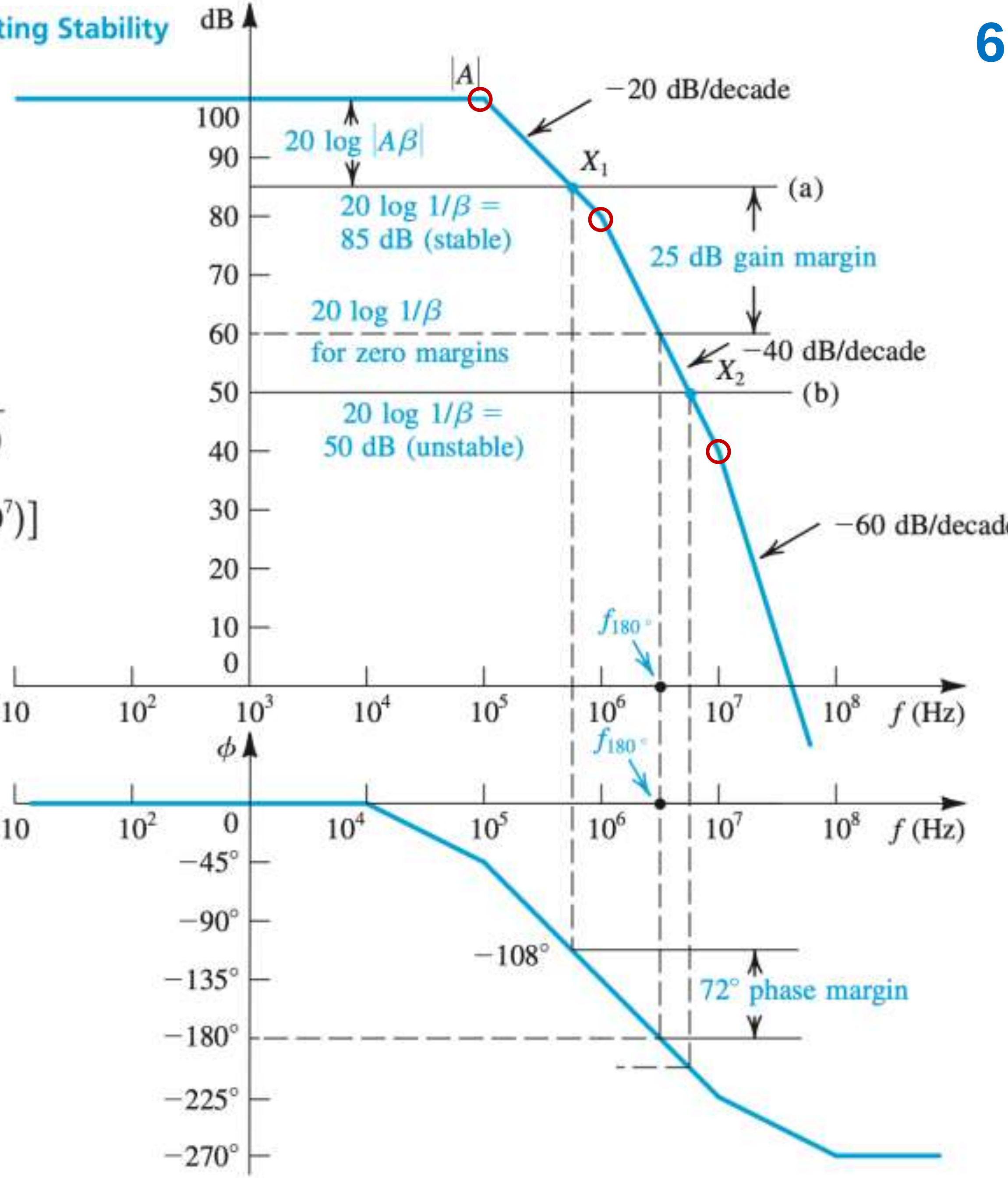

Figure 11.37 Stability analysis using Bode plot of |A|.

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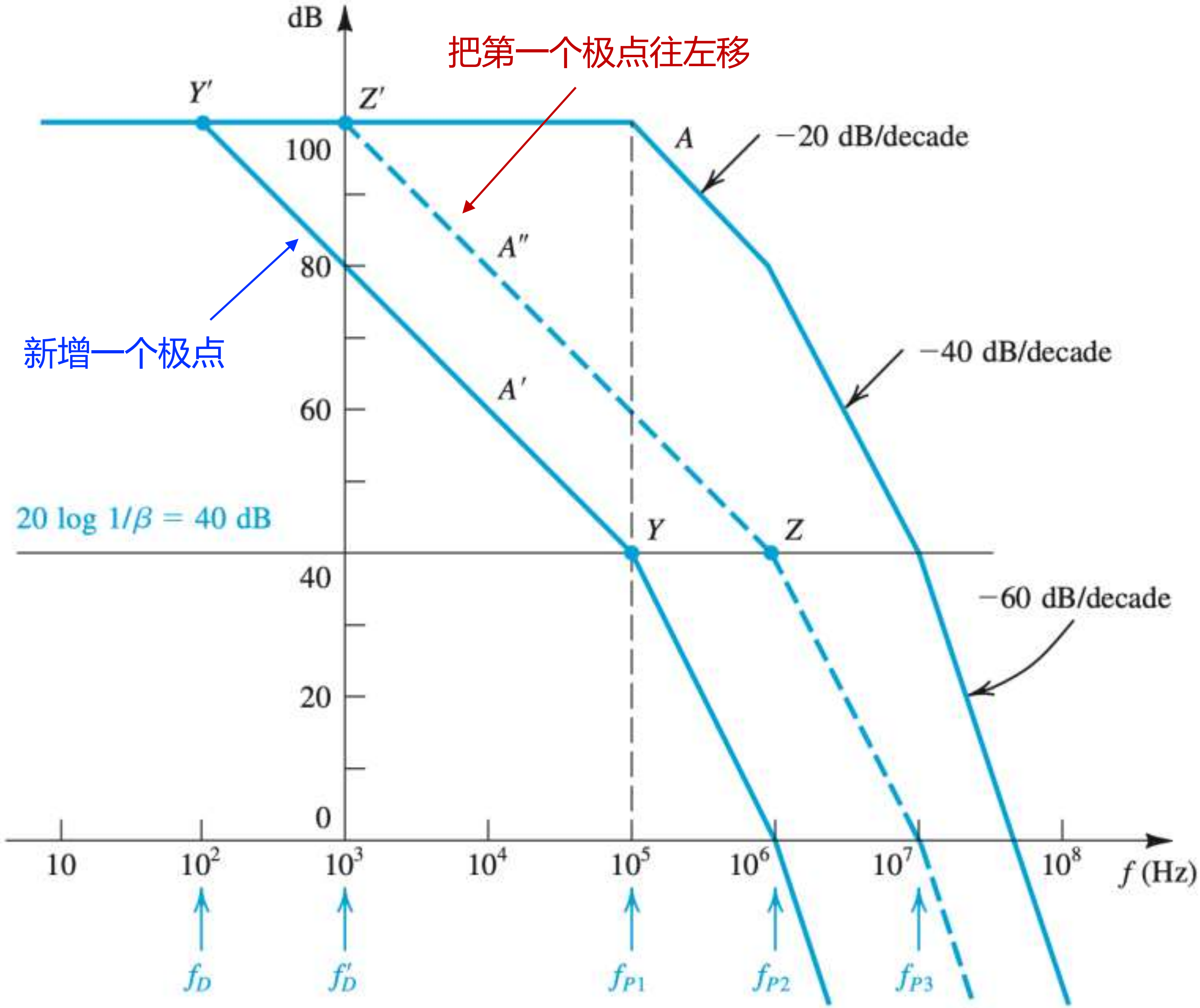

Figure 11.38 Frequency compensation for $\beta = 10^{-2}$. The response labeled A' is obtained by introducing an additional pole at f_D. The A'' response is obtained by moving the original low-frequency pole to f_D'.

作业

11.21 Consider an op amp having a single-pole, open-loop response with $A_0 = 10^5$ and $f_P = 10$ Hz. Let the op amp be ideal otherwise (infinite input impedance, zero output impedance, etc.). If this amplifier is connected in the noninverting configuration with a nominal low-frequency, closed-loop gain of 100, find the frequency at which $|A\beta| = 1$. Also, find the phase margin.

Ans. 10^4 Hz; 90°

11.23 For the amplifier whose open-loop-gain frequency response is shown in Fig. 11.38, find the value of β that results in a phase margin of 45°. What is the corresponding closed-loop gain?

Ans. 10^{-4}; 80 dB

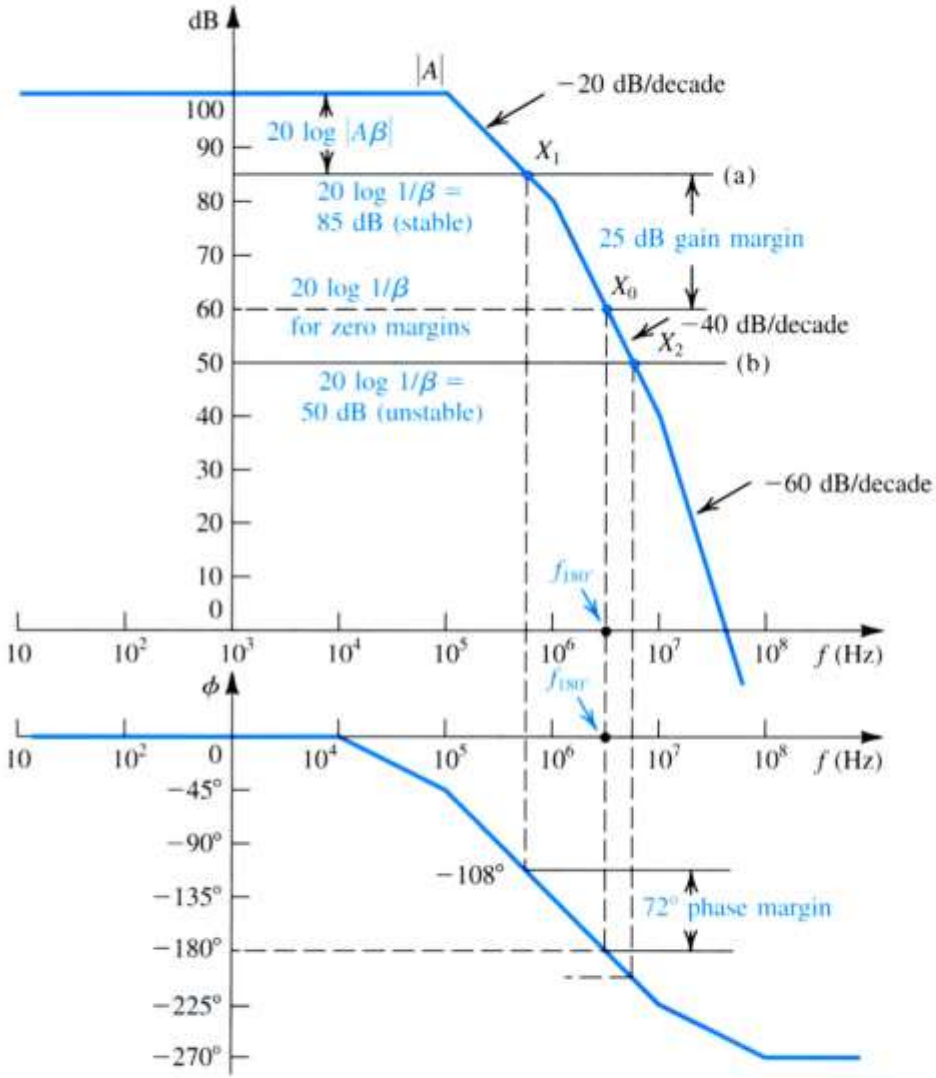

Figure 11.38 Stability analysis using Bode plot of *A*.

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11.24 A multipole amplifier having a first pole at 1 MHz and a dc open-loop gain of 100 dB is to be compensated for closed-loop gains as low as 20 dB by the introduction of a new dominant pole. At what frequency must the new pole be placed?

Ans. 100 Hz