

第五章 反馈

刘鸣

liuming@semi.ac.cn

中国科学院半导体研究所

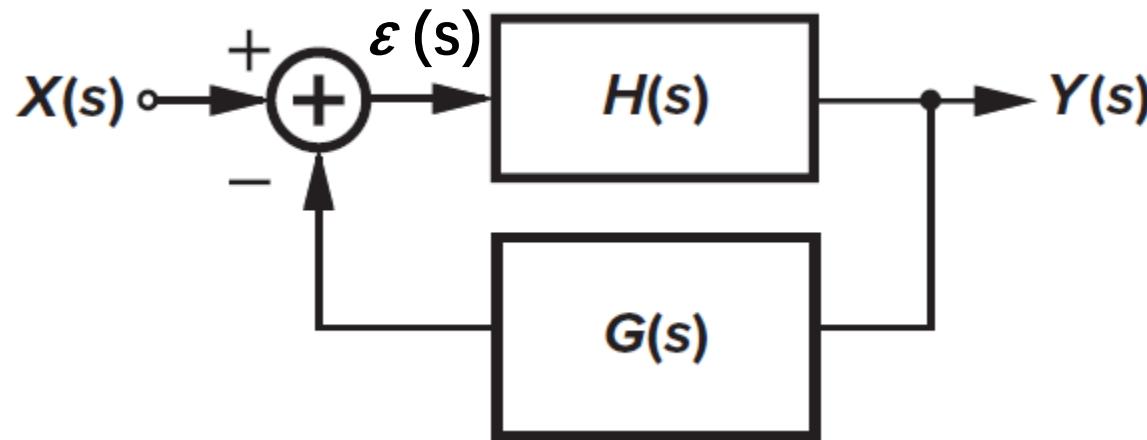
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- 基本概念
- 反馈结构
- 负载影响分析

基本概念

- 基本原理
- 反馈电路特性
- 放大器类型
- 检测及返回机制

基本原理



$$\varepsilon(s) = X(s) - G(s)Y(s)$$

$$Y(s) = H(s)[X(s) - G(s)Y(s)]$$

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

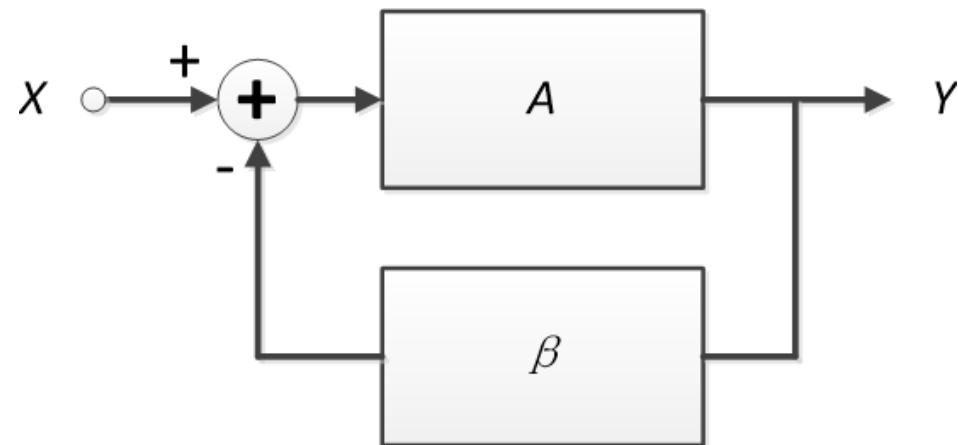
基本原理

- 基本定义

- $X(s)$: 输入;
- $Y(s)$: 输出;
- $\varepsilon(s)$: 误差函数;
- $H(s)$: 前馈网络; 开环传输函数; 开环增益;
- $G(s)$: 反馈网络; 用反馈系数 β 代替 (与频率无关) ;
- $Y(s)/X(s)$: 闭环传输函数; 闭环增益;
- $G(s)H(s)$: 环路增益;

反馈电路特性-1

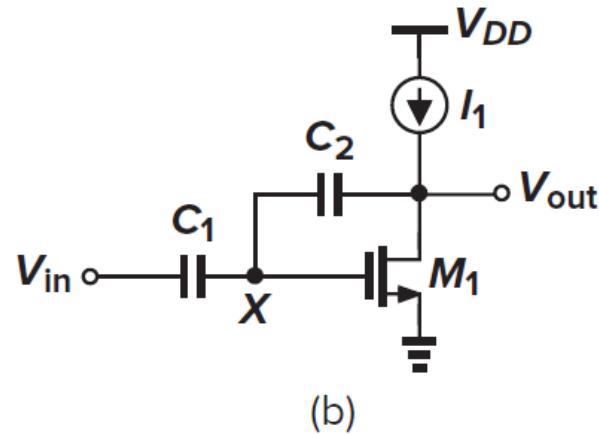
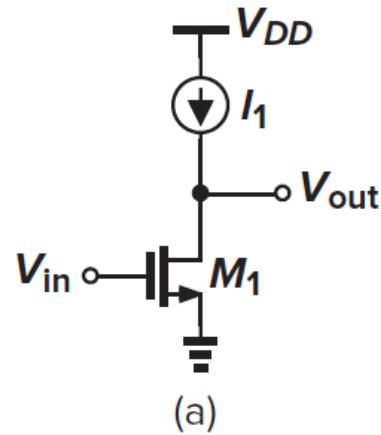
- 增益敏感度降低



$$A_{CL} = \frac{Y}{X} = \frac{A}{1 + \beta A} = \frac{1}{\beta} \cdot \frac{\beta A}{1 + \beta A} \approx \frac{1}{\beta} \left(1 - \frac{1}{\beta A} \right) \approx \frac{1}{\beta} \quad \text{If } \beta A \gg 1$$

反馈电路特性-1

- 跨导 g_{m1} 和输出电阻 r_{o1} 随工艺和温度改变，增益不稳定，通过反馈使得增益灵敏度降低，闭环增益对器件参数变化不敏感



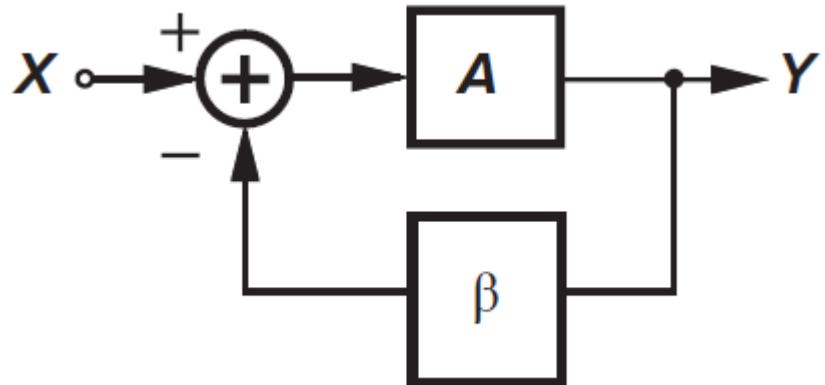
$$\frac{V_{out}}{V_{in}} = -\frac{1}{\left(1 + \frac{1}{g_{m1}r_{o1}}\right)\frac{C_2}{C_1} + \frac{1}{g_{m1}r_{o1}}}$$

If $g_{m1}r_{o1} \gg 1$

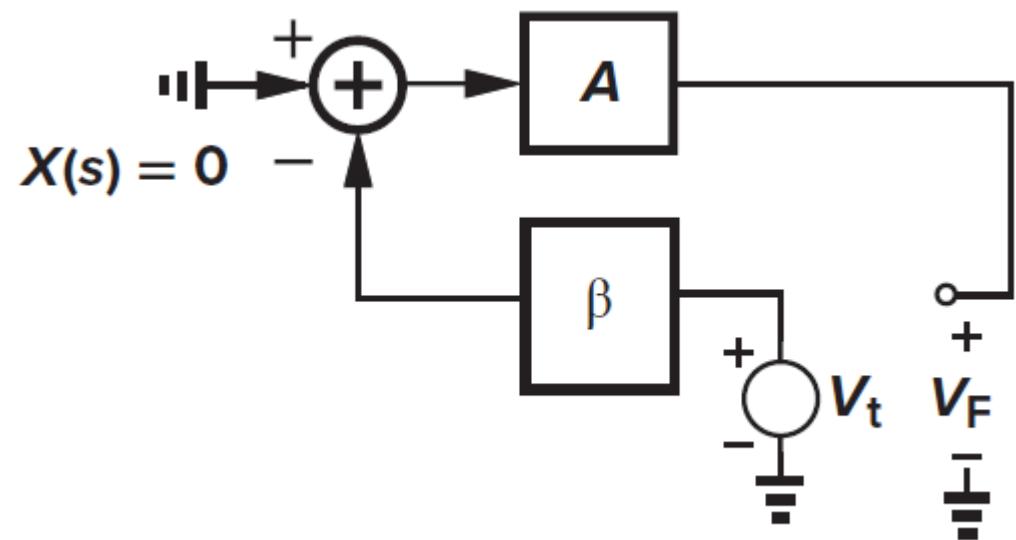
$$\frac{V_{out}}{V_{in}} = -\frac{C_1}{C_2}$$

反馈电路特性-1

- 环路增益计算

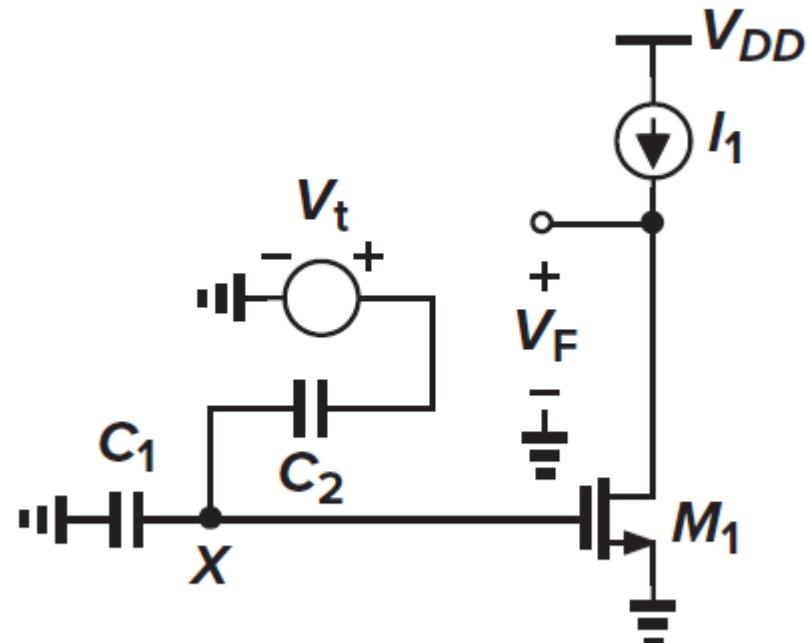


⇒



$$V_t \beta (-1)A = V_F \Rightarrow V_F / V_t = -\beta A$$

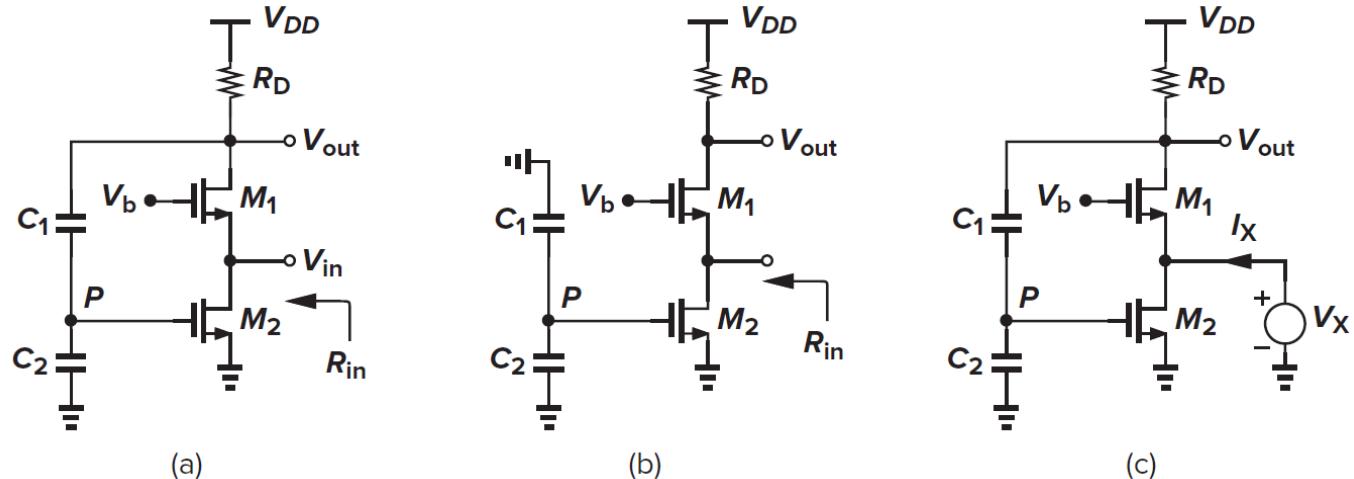
反馈电路特性-1



$$\frac{V_F}{V_t} = -\frac{C_2}{C_1 + C_2} g_{m1} r_{o1}$$

反馈电路特性-2

- 阻抗变化



$$R_{in,open} = \frac{1}{g_{m1} + g_{mb1}} \quad (1)$$

$$V_{out} = (g_{m1} + g_{mb1})V_X R_D \quad (2)$$

$$V_P = V_{out} \frac{C_1}{C_1 + C_2} \quad (3)$$

$$= (g_{m1} + g_{mb1}) V_X R_D \frac{C_1}{C_1 + C_2}$$

$$I_X = (g_{m1} + g_{mb1})V_X + g_{m2}(g_{m1} + g_{mb1})\frac{C_1}{C_1 + C_2}R_D V_X$$

$$= (g_{m1} + g_{mb1}) \left(1 + g_{m2} R_D \frac{C_1}{C_1 + C_2} \right) V_X \quad (4)$$

$$R_{in,closed} = V_X/I_X$$

$$= \frac{1}{g_{m1} + g_{mb1}} \frac{1}{1 + g_{m2} R_D \frac{C_1}{C_1 + C_2}} \quad (5)$$

反馈电路特性-2

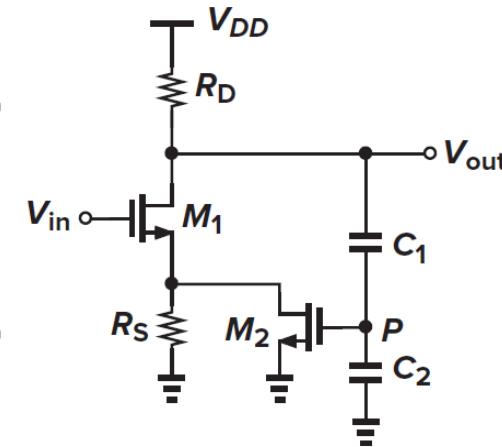
例：

$$I_{D1} = V_X \frac{C_1}{C_1 + C_2} g_{m2} \frac{R_S}{R_S + \frac{1}{g_{m1} + g_{mb1}}}$$

$$I_X = V_X / R_D + I_{D1}$$

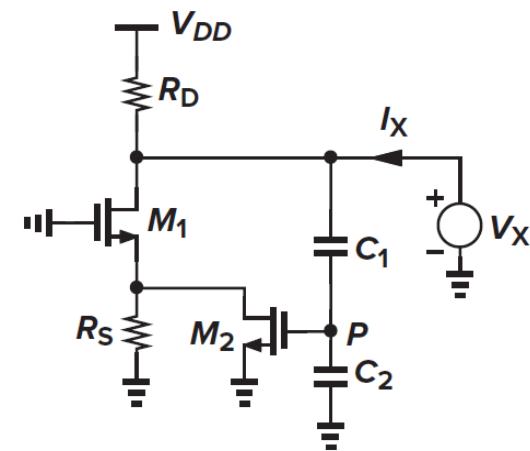
$$\frac{V_X}{I_X} = \frac{R_D}{1 + \frac{g_{m2} R_S (g_{m1} + g_{mb1}) R_D}{(g_{m1} + g_{mb1}) R_S + 1} \frac{C_1}{C_1 + C_2}} \quad (3)$$

(1)



(2)

(a)



(b)

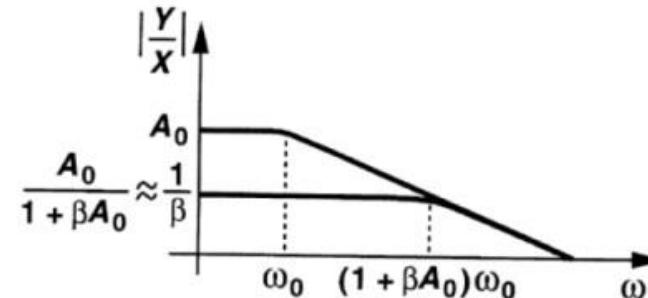
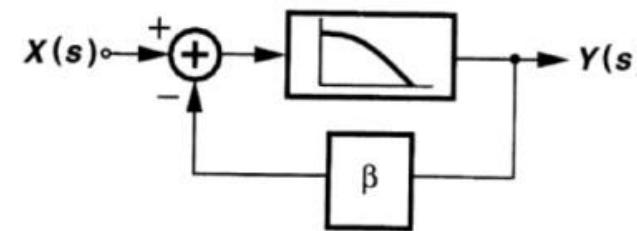
反馈电路特性-3

- 带宽改变

$$A(s) = \frac{A_0}{1 + \frac{s}{\omega_0}}$$

ω_0 : 3dB带宽
 A_0 : 低频增益

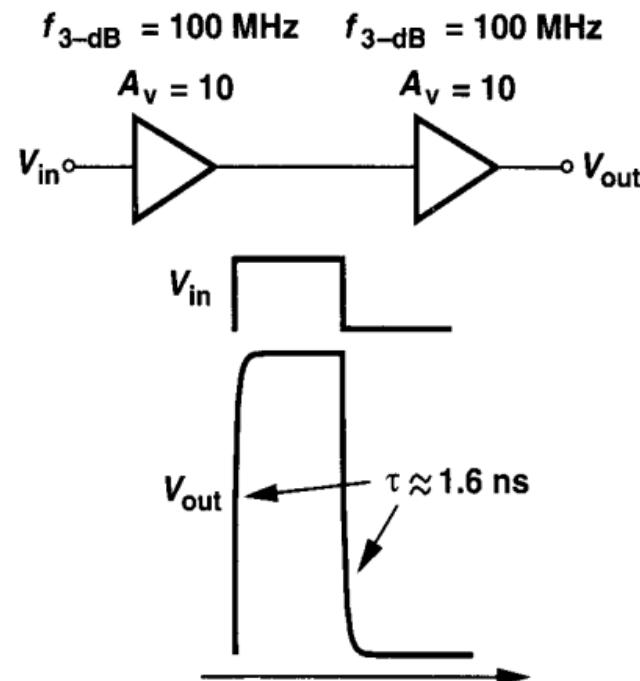
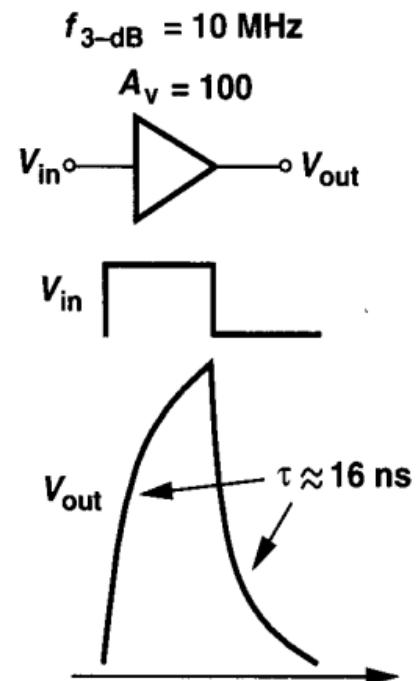
$$\frac{Y(s)}{X(s)} = \frac{A(s)}{1 + \beta A(s)} = \frac{\frac{A_0}{1 + \beta A_0}}{1 + \frac{s}{(1 + \beta A_0)\omega_0}}$$



带宽扩展到 $(1 + \beta A_0)\omega_0$, 以增益减小 $(1 + \beta A_0)$ 倍为代价,
所以增益带宽积 (GBW) 保持不变

反馈电路特性-3

- 例

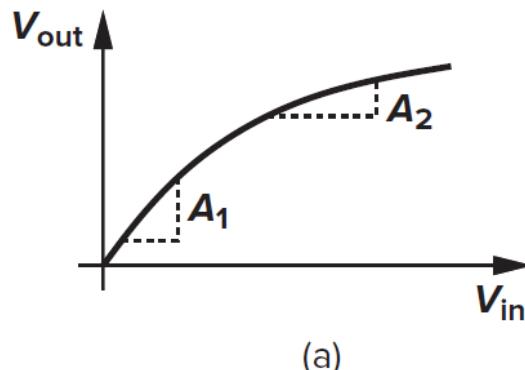


放大一个20MHz的方波采用的方法 (a) 一个10-MHz放大器;
(b) 两个100-MHz反馈放大器的级联

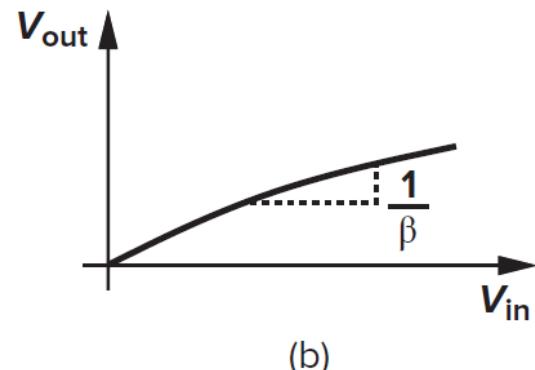
反馈电路特性-4

- 减少非线性

$$r_{open} = \frac{A_2}{A_1} \quad (1)$$



(a)

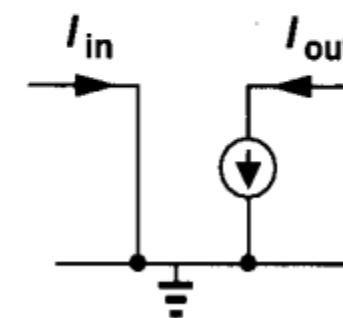
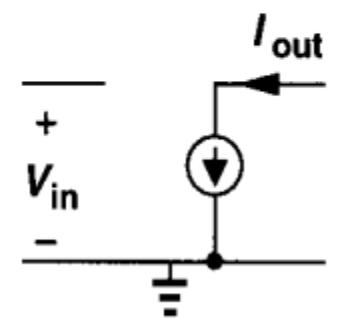
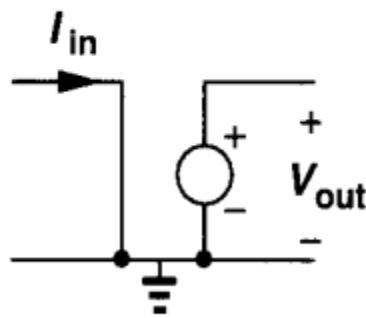
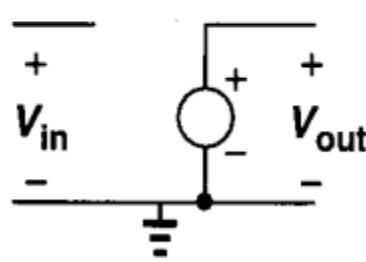
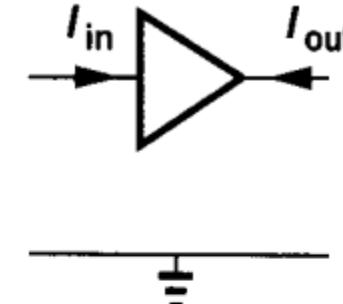
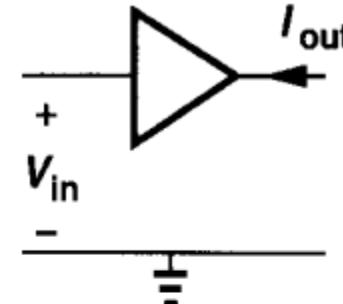
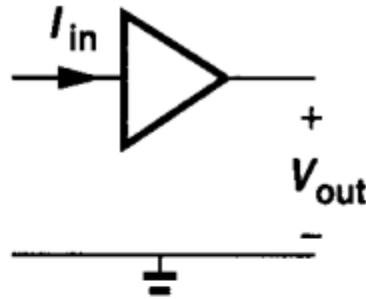
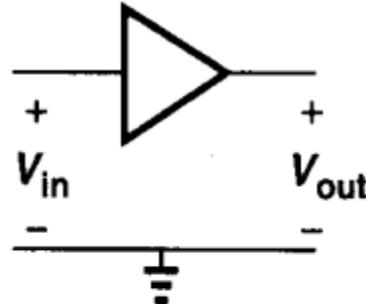


(b)

$$r_{closed} \approx 1 - \frac{\frac{1}{\beta A_2} - \frac{1}{\beta A_1}}{1 + \frac{1}{\beta A_2}}$$

$$\begin{aligned} r_{closed} &= \frac{\frac{A_2}{1 + \beta A_2}}{\frac{A_1}{1 + \beta A_1}} = \frac{1 + \frac{1}{\beta A_1}}{1 + \frac{1}{\beta A_2}} \quad (2) \\ &\approx 1 - \frac{A_1 - A_2}{1 + \beta A_2} \frac{1}{A_1} \quad (3) \\ &\approx 1 - \frac{\Delta A}{1 + \beta A_2} \frac{1}{A_1} \end{aligned}$$

放大器类型



(a)

(b)

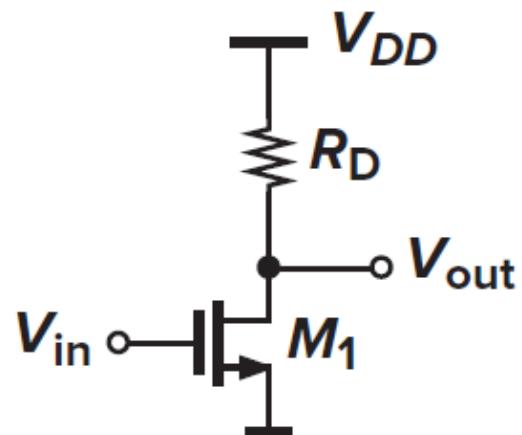
(c)

(d)

- 检测电压信号的电路，必须有高输入阻抗，检测电流信号的电路必须有低输入阻抗；
- 产生电压信号的电路，必须有低输出阻抗，输出电流信号的电路必须有高输出阻抗；

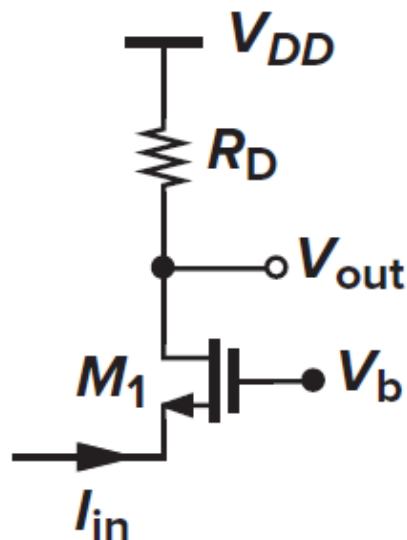
放大器类型

- 四种简单的放大器



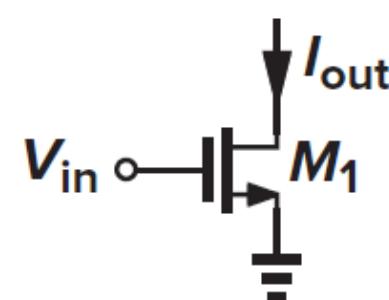
(a)

电压-电压



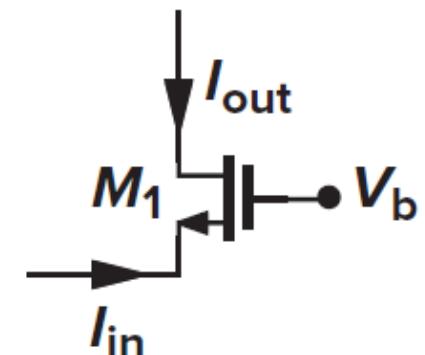
(b)

电流-电压



(c)

电压-电流

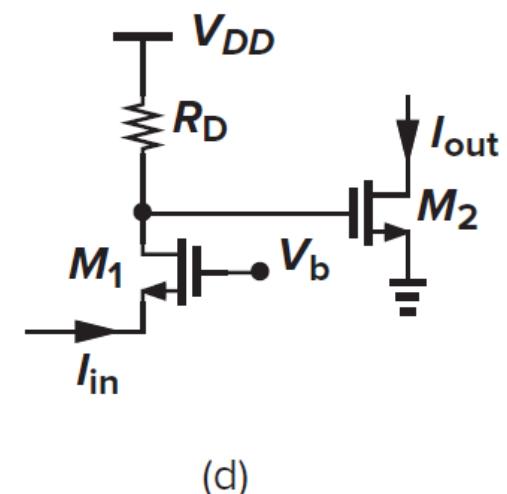
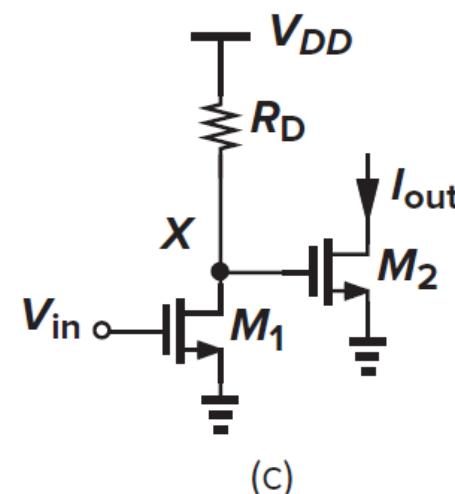
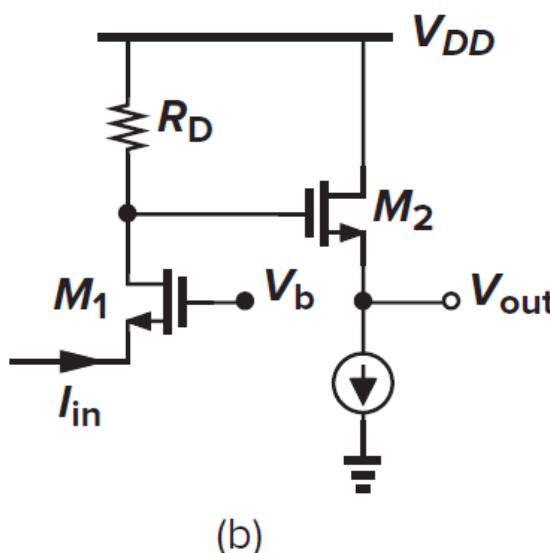
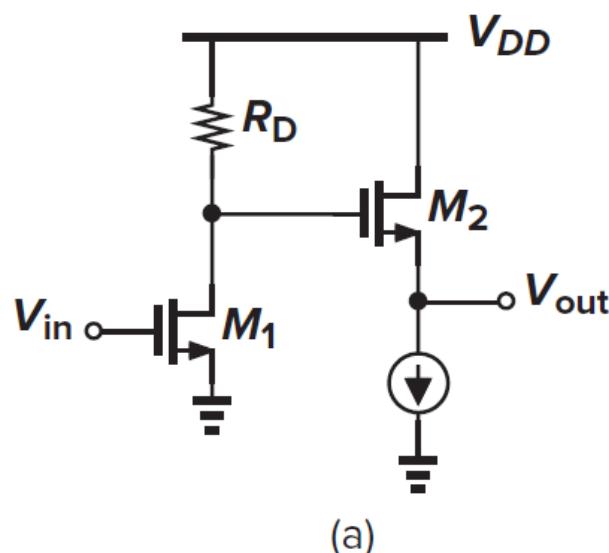


(d)

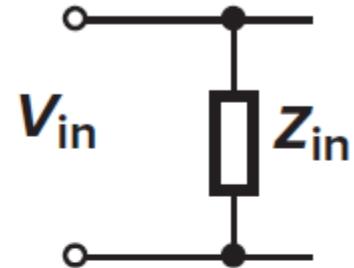
电流-电流

改进放大器

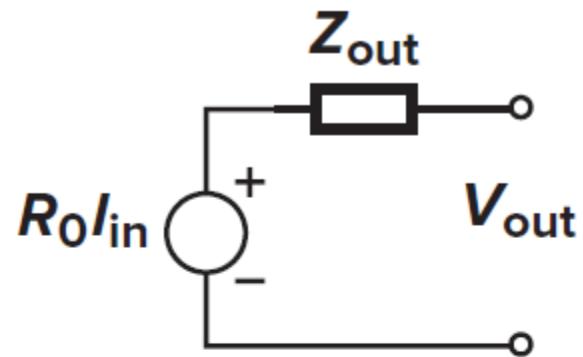
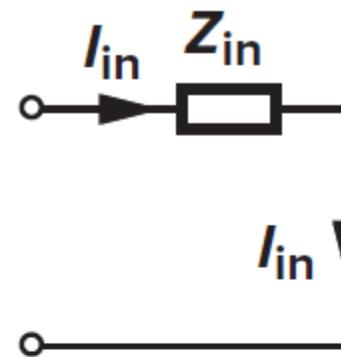
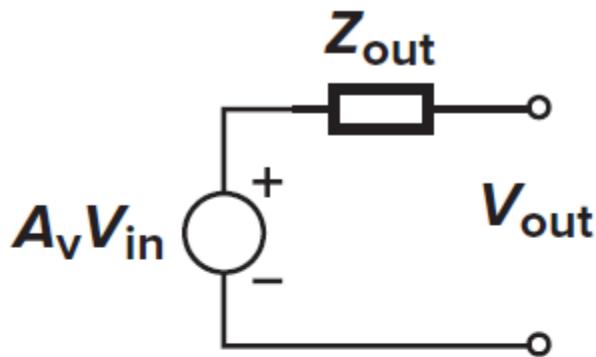
- 输出电阻改变和增益加大



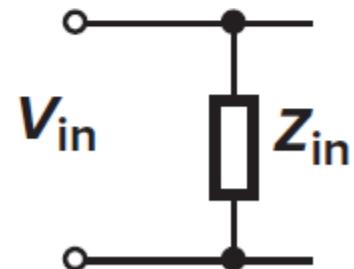
非理想放大器



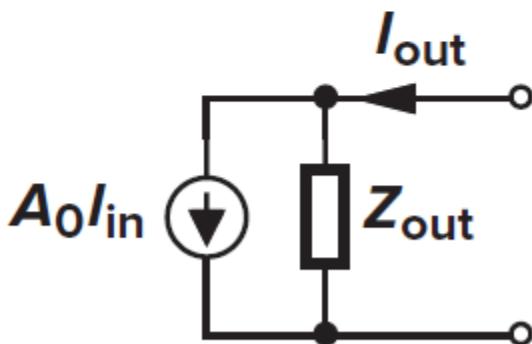
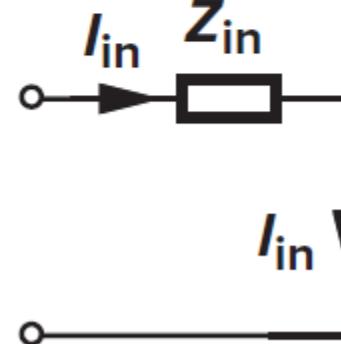
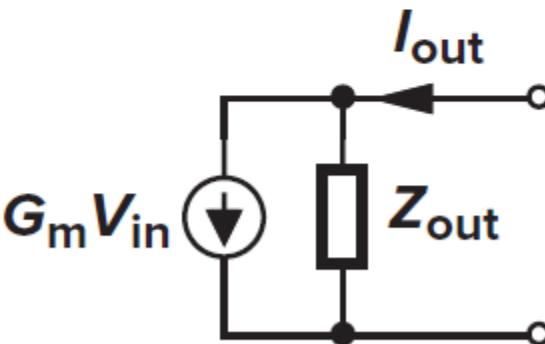
(a)



(b)



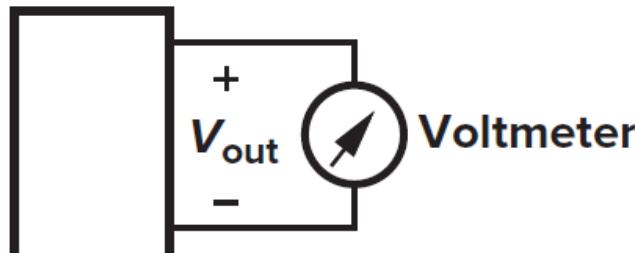
(c)



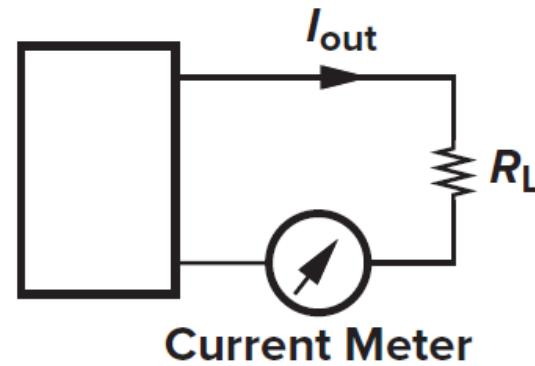
(d)

检测及返回机制

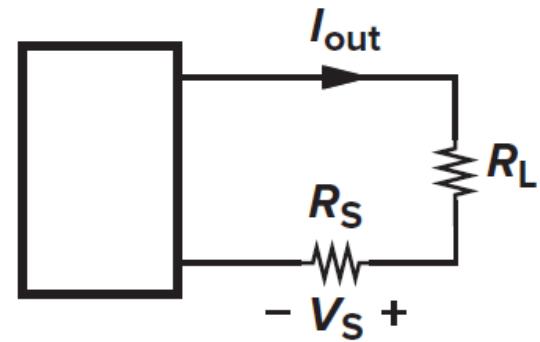
- 检测机制：电压表和电流表，电阻检测电流



(a)



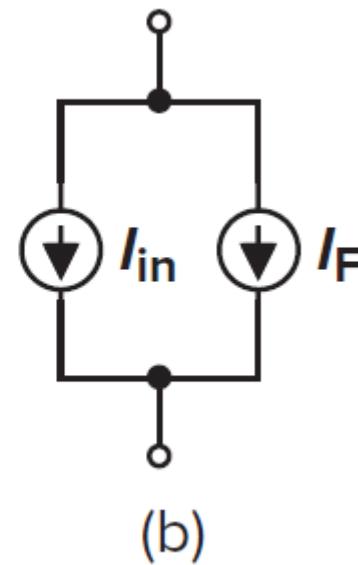
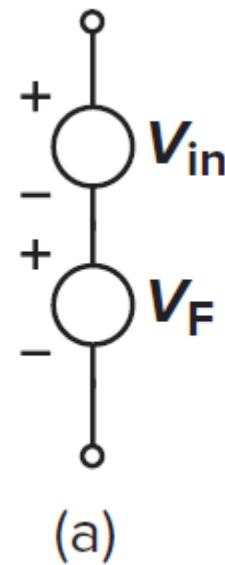
(b)



(c)

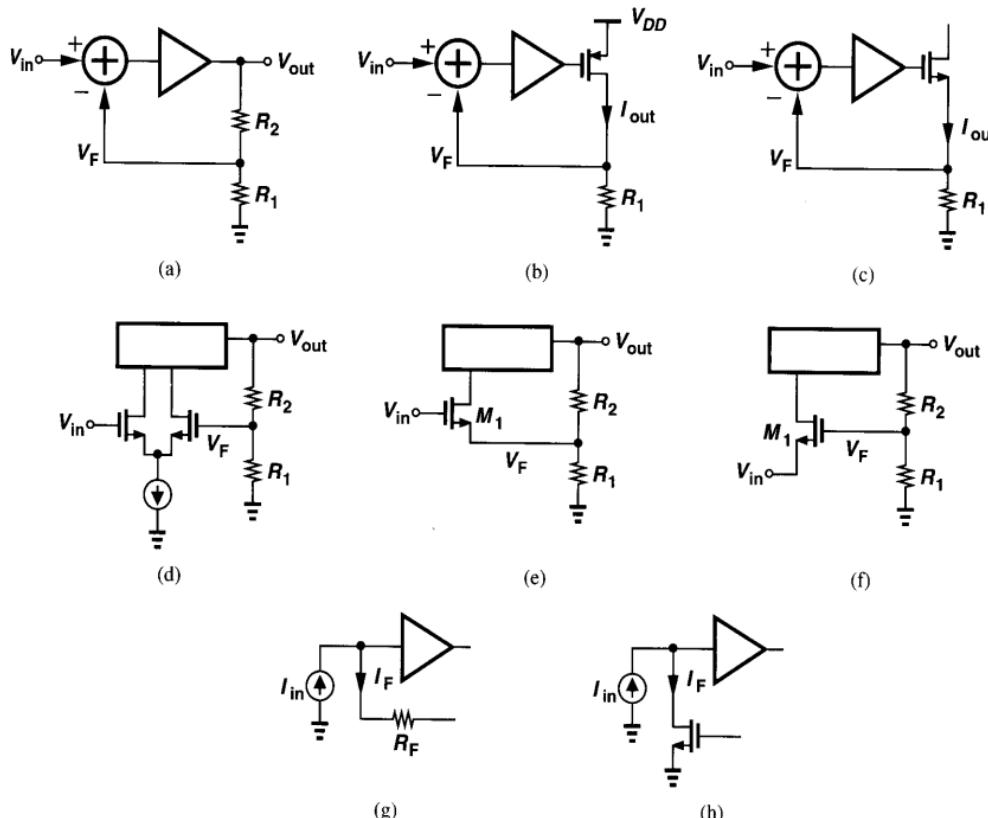
检测及返回机制

- 电压和电流返回方法
 - 电压返回为串联
 - 电流返回为并联



检测及返回机制

- 例



- (a) 电压-电压
- (b) 电流-电压
- (c) 电流-电压
- (d) 电压-电压
- (e) 电压-电压
- (f) 电压-电压
- (g) 和 (h) 电流相减

输出端-输入端	输入端-输出端
电压-电压	串联-并联
电压-电流	并联-并联
电流-电流	并联-串联
电流-电压	串联-串联

目录

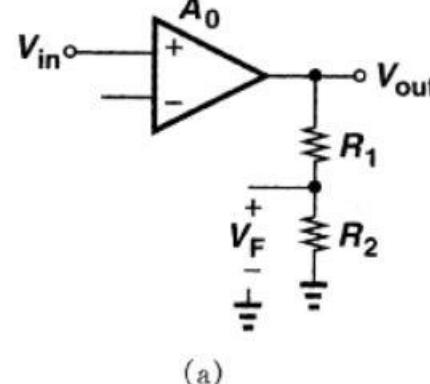
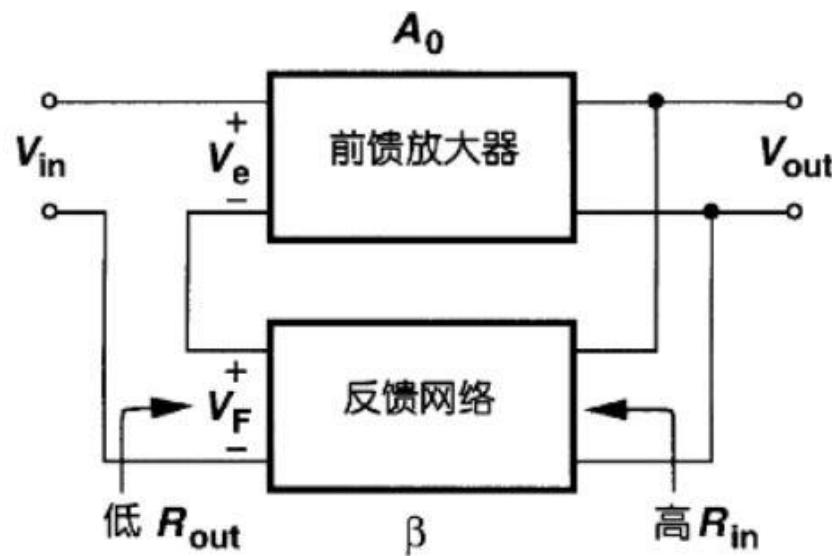
- 基本概念
- 反馈结构
- 负载影响分析

反馈结构

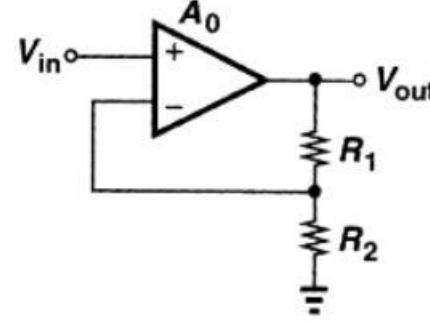
- 电压-电压 (串联-并联)
- 电流-电压 (串联-串联)
- 电压-电流 (并联-并联)
- 电流-电流 (并联-串联)

反馈结构 — 电压-电压反馈

- 电压-电压：输出端并联，采样电压以串联方式接入输入，成为总体输入电压的一部分。



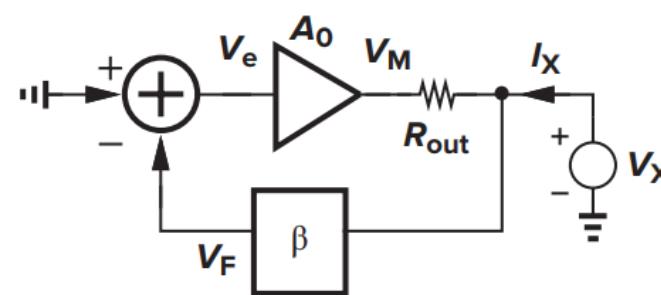
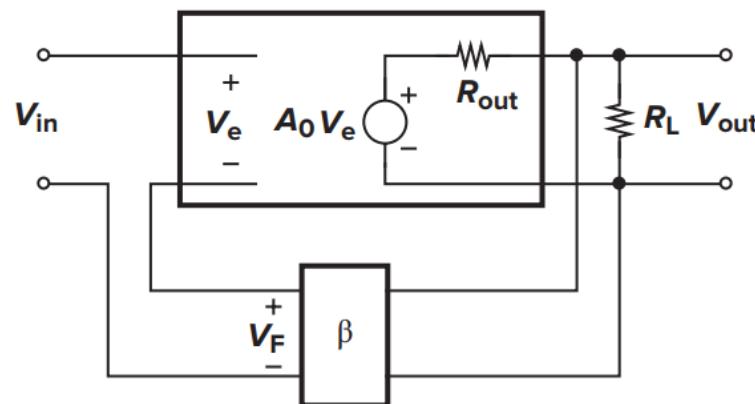
(a)



(b)

反馈结构 — 电压-电压反馈

- 输出电阻变化



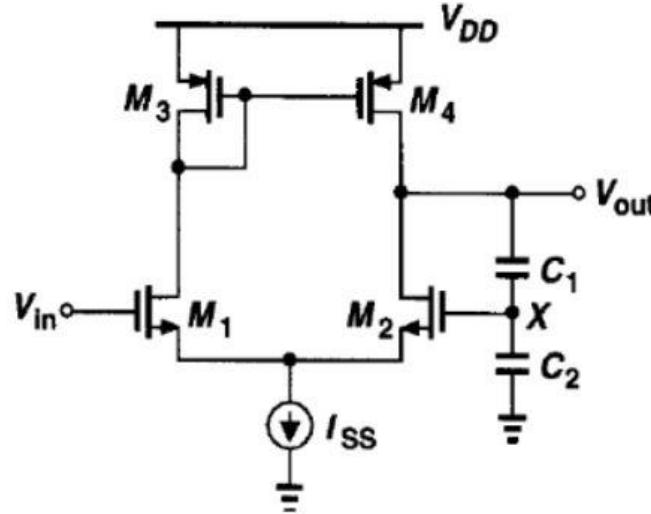
$$I_X = \frac{V_X - V_M}{R_{out}} = \frac{V_X - (-\beta A_0 V_X)}{R_{out}}$$

$$R_{out,CL} = \frac{V_X}{I_X} = \frac{R_{out}}{1 + \beta A_0}$$

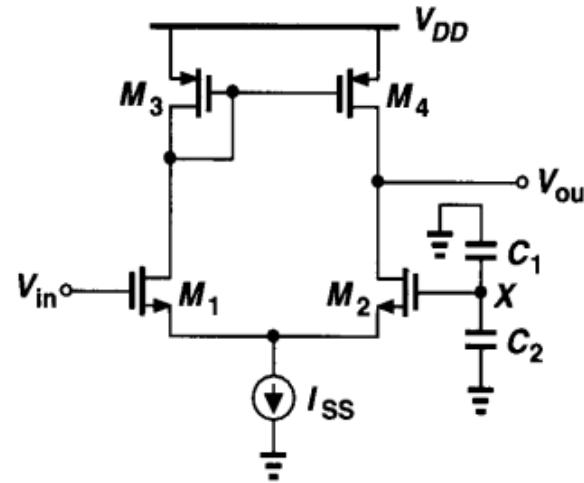
输出并联，减小了输出电阻，更接近一个恒压源

反馈结构 — 电压-电压反馈

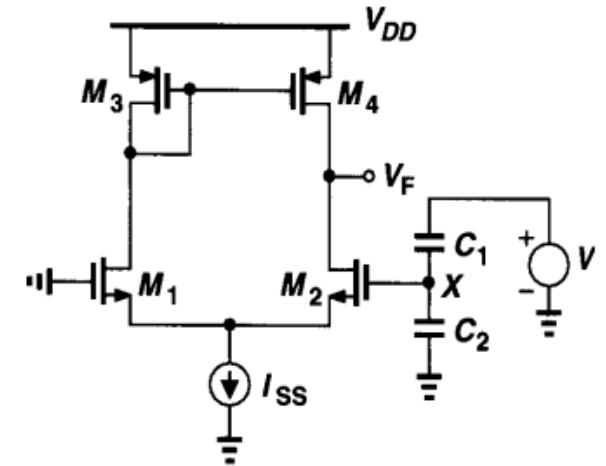
- 例



(a)



(b)



(c)

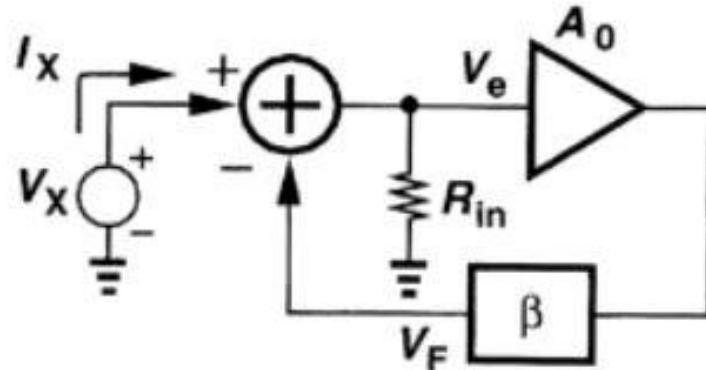
$$\beta = \frac{C_1}{C_1 + C_2} \quad A_{0,open} = g_{m1}(r_{o2} \parallel r_{o4})$$

$$R_{out,open} = (r_{o2} \parallel r_{o4}) \quad A_{close} = \frac{A_{0,open}}{1 + \beta A_{0,open}}$$

$$R_{out,cl} = \frac{R_{out,open}}{1 + \beta A_{0,open}} \approx \left(1 + \frac{C_2}{C_1}\right) \frac{1}{g_{m1}}$$

反馈结构 — 电压-电压反馈

- 输入电阻的变化



$$V_e = I_X R_{in}$$

$$V_F = \beta A_0 I_X R_{in}$$

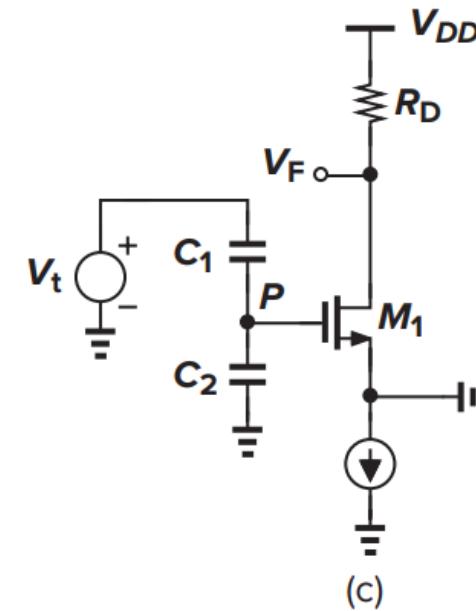
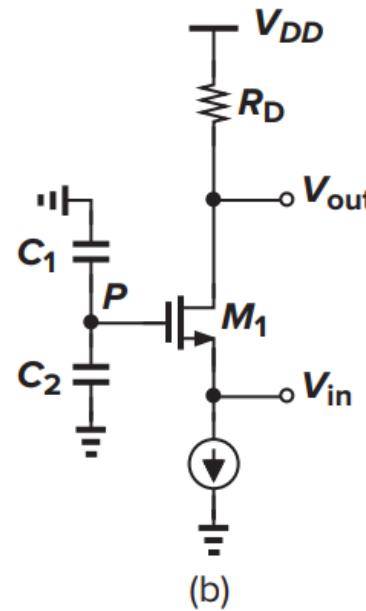
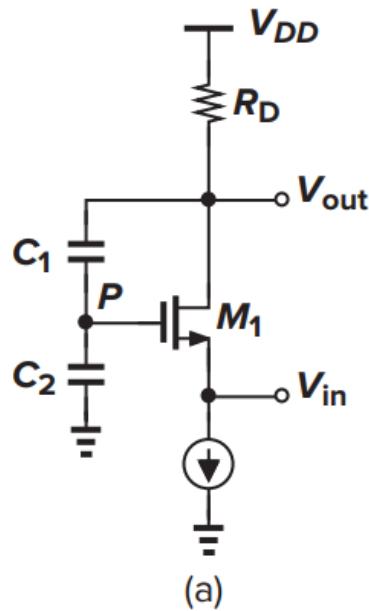
$$V_e = V_X - V_F$$

$$\frac{V_X}{I_X} = R_{in}(1 + \beta A_0)$$

输入串联，减小了输入电压，增大了输入电阻；接近理想电压放大器。

反馈结构 — 电压-电压反馈

- 例

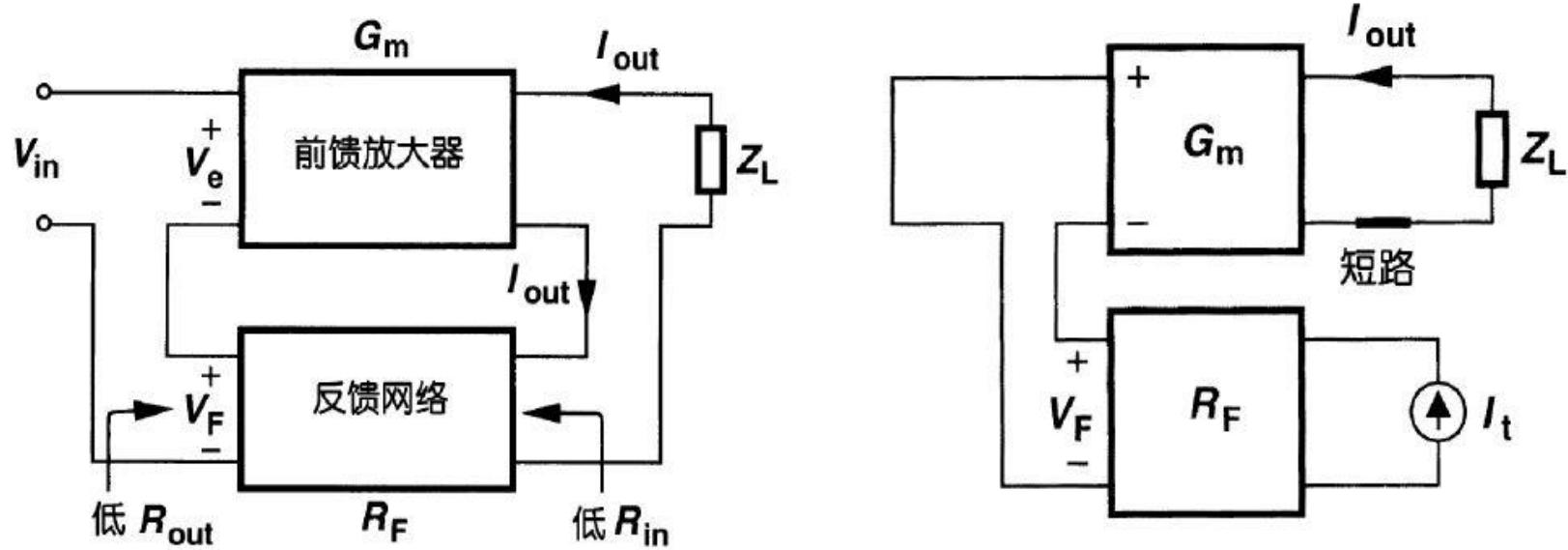


$$R_{in,open} = (g_{m1} + g_{mb1})^{-1}$$

$$V_F/V_T = -g_{m1}R_D C_1 / (C_1 + C_2)$$

$$R_{in,closed} = \frac{1}{g_{m1} + g_{mb1}} \left(1 + \frac{C_1}{C_1 + C_2} g_{m1} R_D \right)$$

反馈结构 — 电流-电压反馈



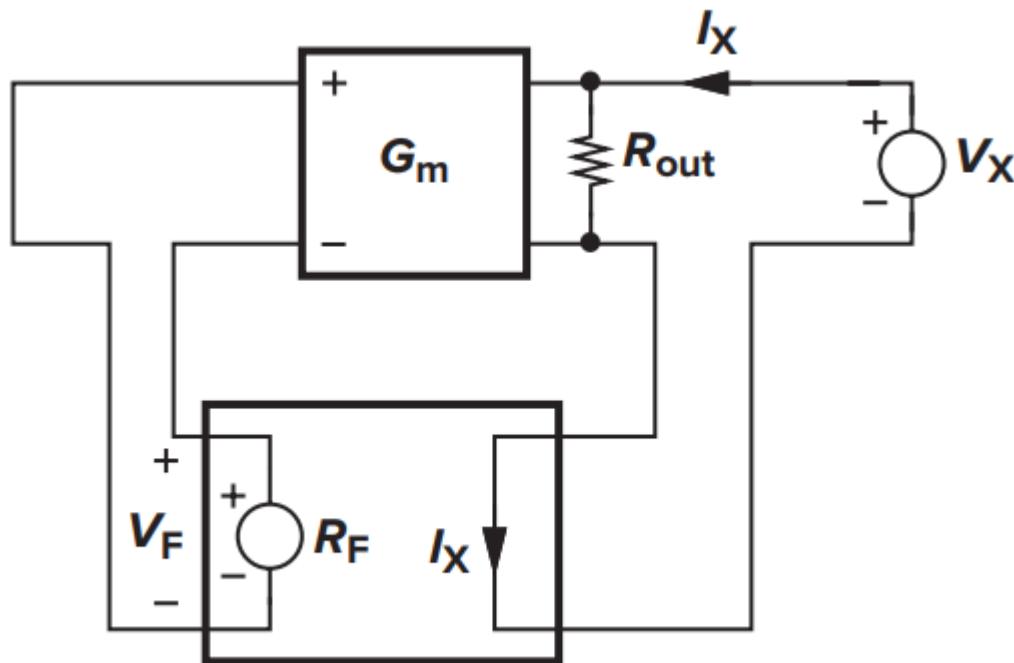
(a) 电流-电压反馈

(b) 反馈环路增益计算

$$\frac{I_{out}}{V_{in}} = \frac{G_m}{1 + G_m R_F} \quad G_m: \text{跨导}$$

反馈结构 — 电流-电压反馈

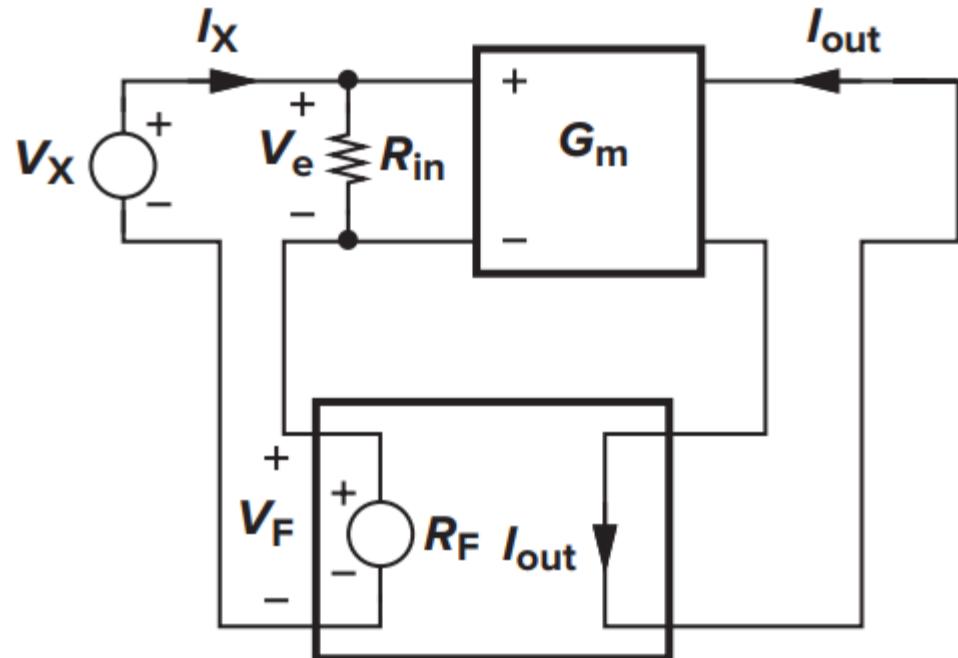
- 输出电阻变化



$$\frac{V_X}{I_X} = R_{out}(1 + G_m R_F)$$

反馈结构 — 电流-电压反馈

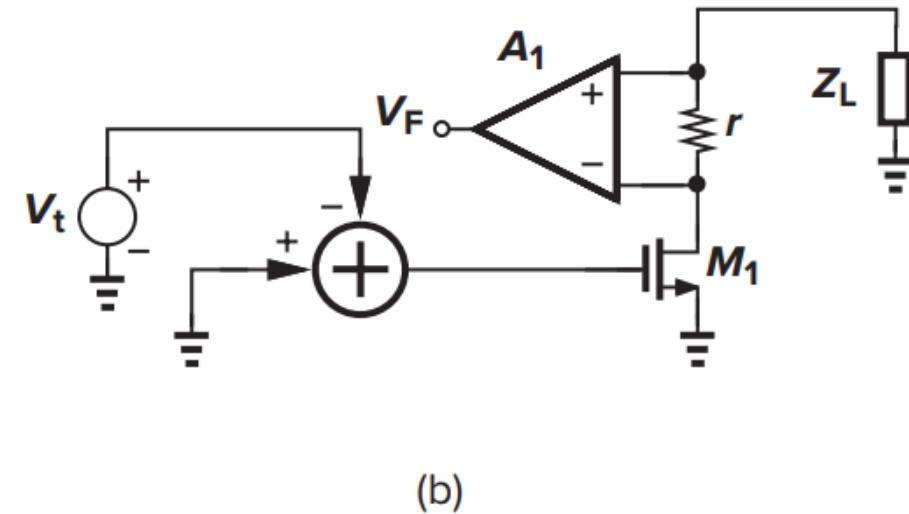
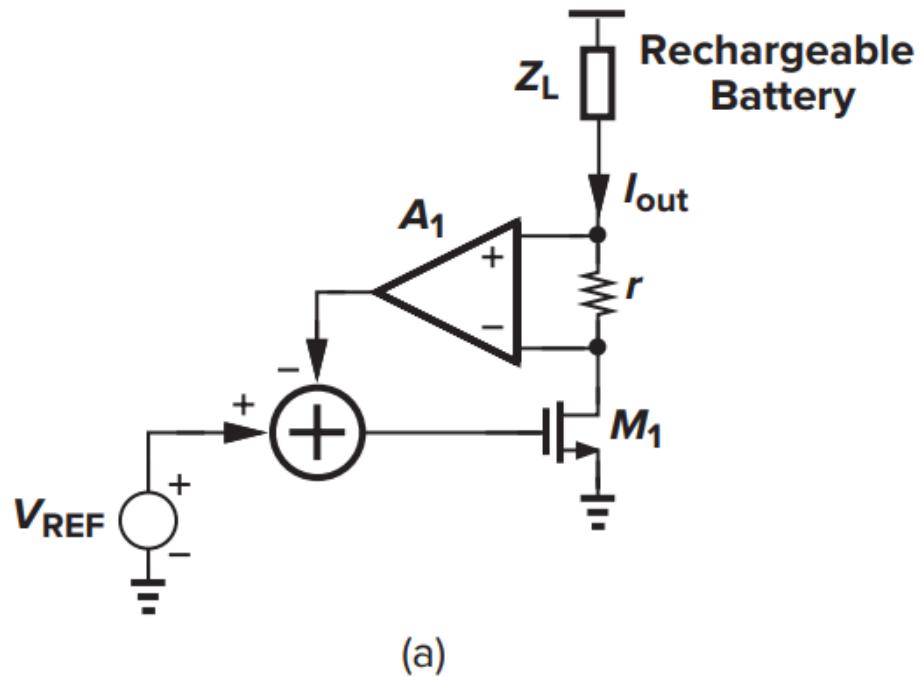
- 输入电阻变化



$$\frac{V_x}{I_X} = R_{in}(1 + G_m R_F)$$

反馈结构 — 电流-电压反馈

- 例：



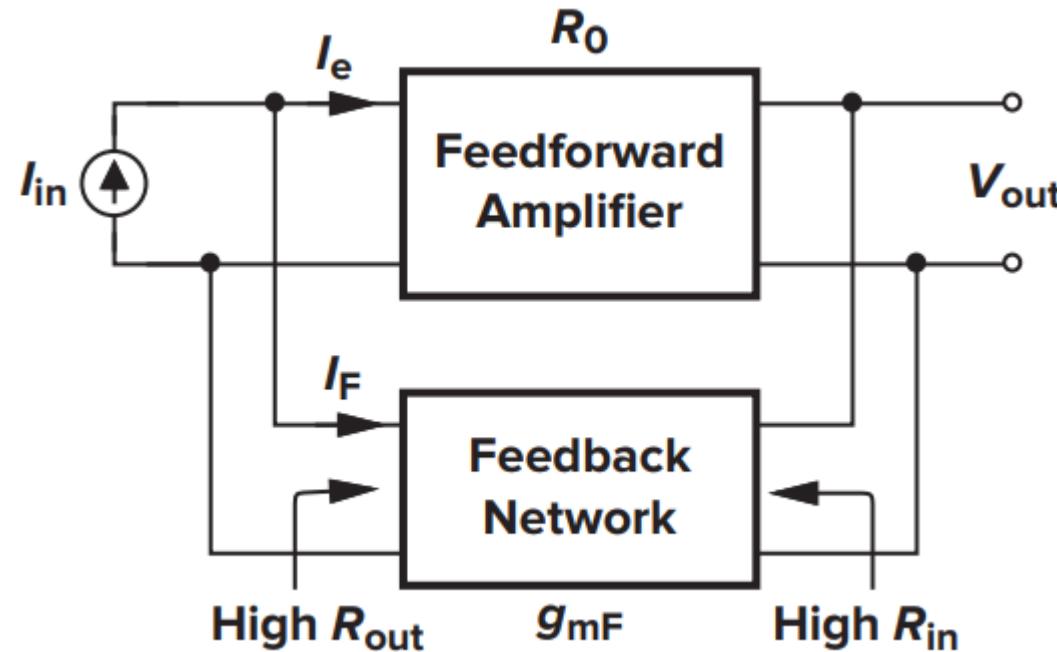
$$I_{out} \approx (V_{REF}/A_1)/r$$

$$\frac{V_F}{V_t} \approx -g_m r A_1$$

$$R_{out,closed} = (1 + g_m r A_1)(r_o + r)$$

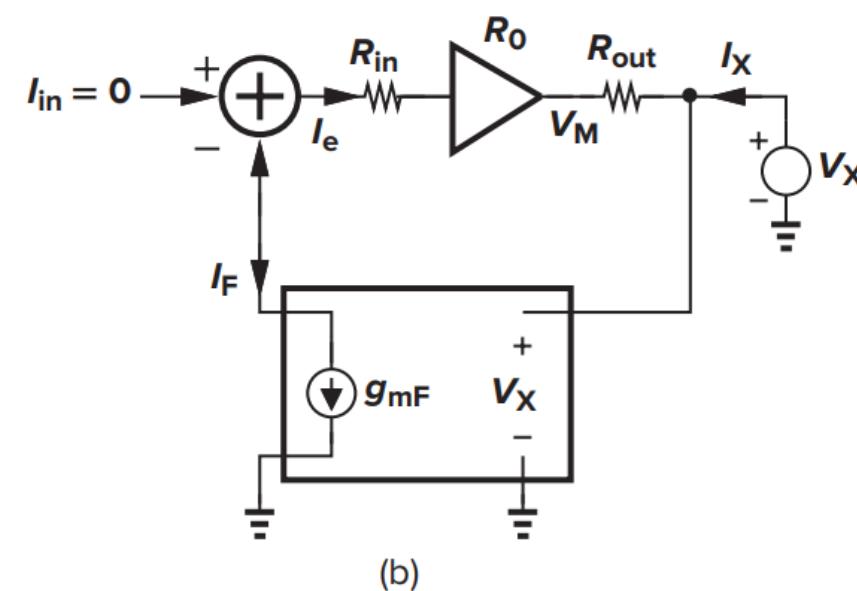
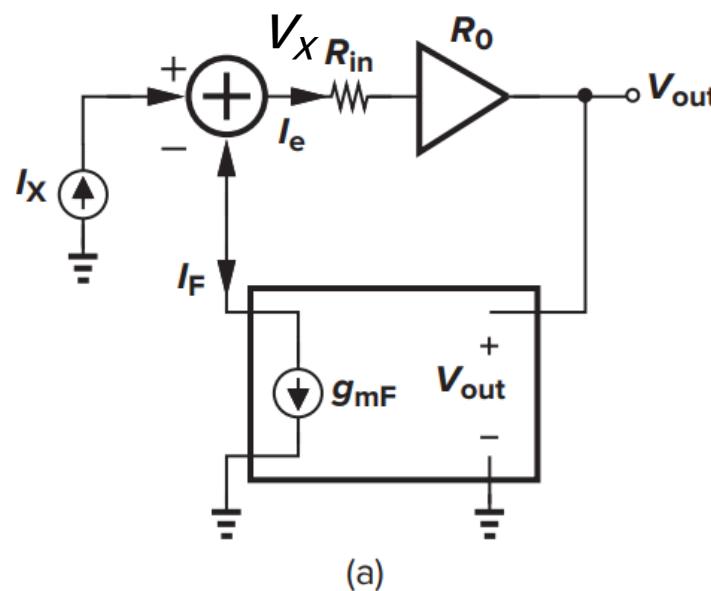
反馈结构 — 电压-电流反馈

- 结构



反馈结构 — 电压-电流反馈

- 输入和输出电阻计算

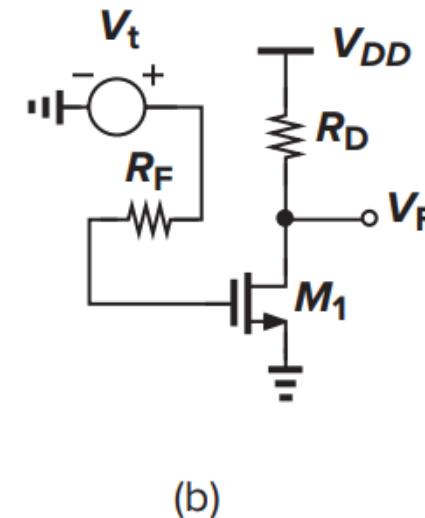
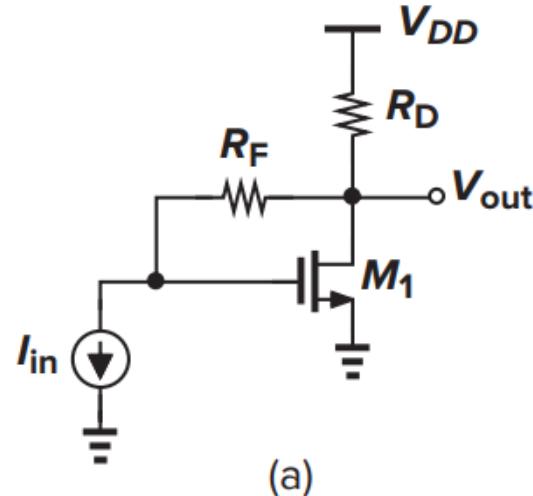


$$\frac{V_X}{I_X} = \frac{R_{in}}{1 + g_{mF} R_0}$$

$$\frac{V_X}{I_X} = \frac{R_{out}}{1 + g_{mF} R_0}$$

反馈结构 — 电压-电流反馈

- 例

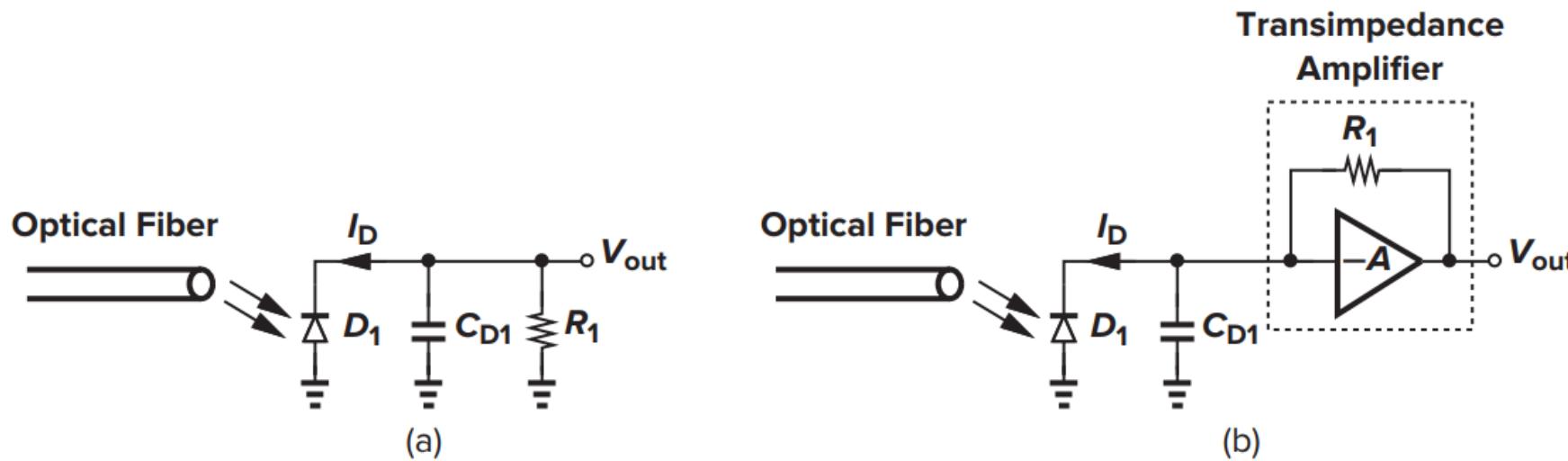


$$R_{in,closed} = \frac{R_F}{1 + g_m R_D}$$

$$\begin{aligned} R_{out,closed} &= \frac{R_D}{1 + g_m R_D} \\ &= \frac{1}{g_m} || R_D \end{aligned}$$

反馈结构 — 电压-电流反馈

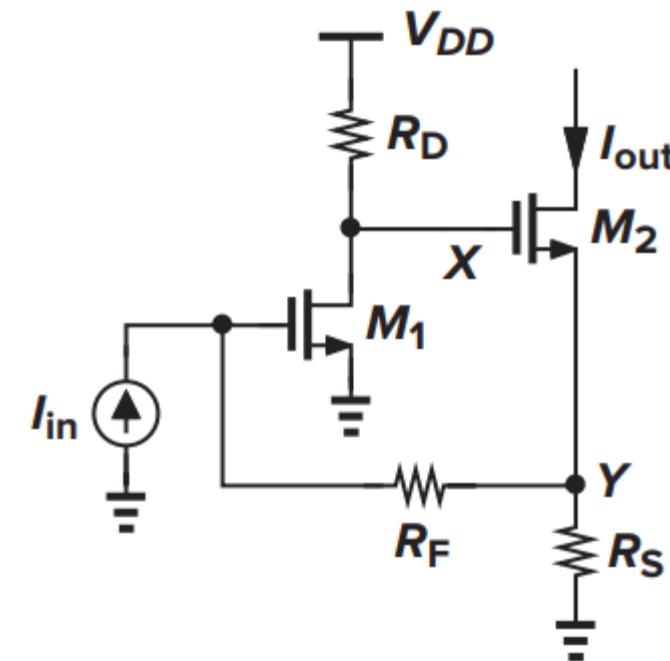
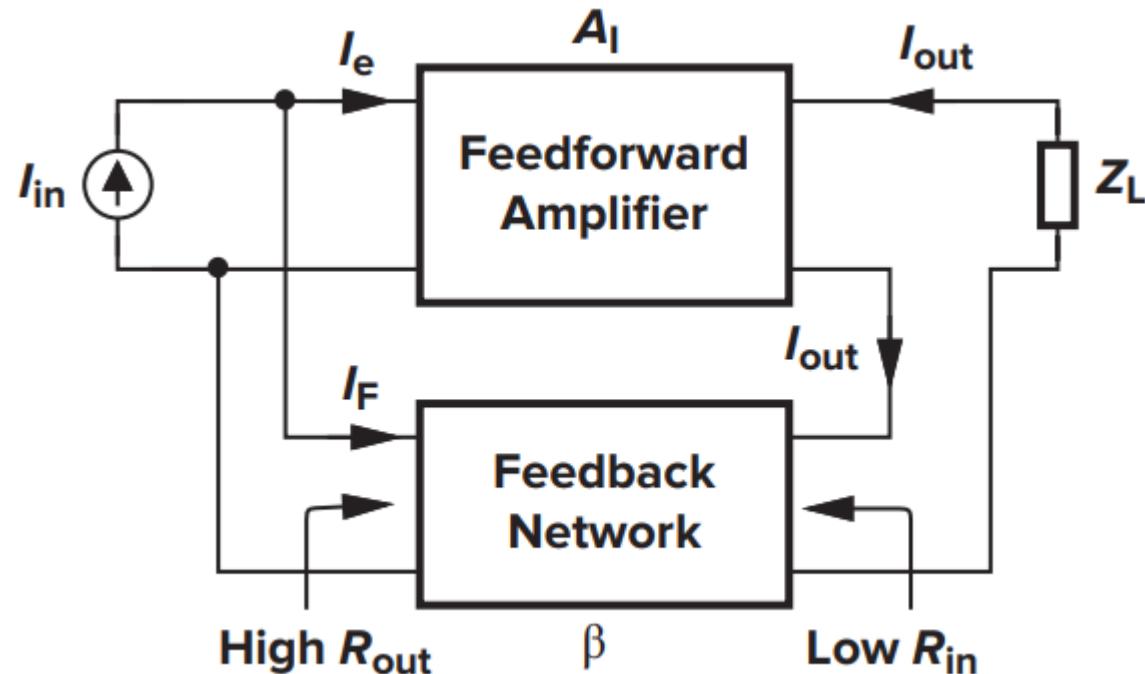
- 例：光敏二极管检测电路



$$R_{in} = R_1/(1 + A) \quad V_{out} \approx -R_1 I_D \quad BW = (1 + A)/2\pi R_1 C_{D1}$$

反馈结构 — 电流-电流反馈

- 结构



目录

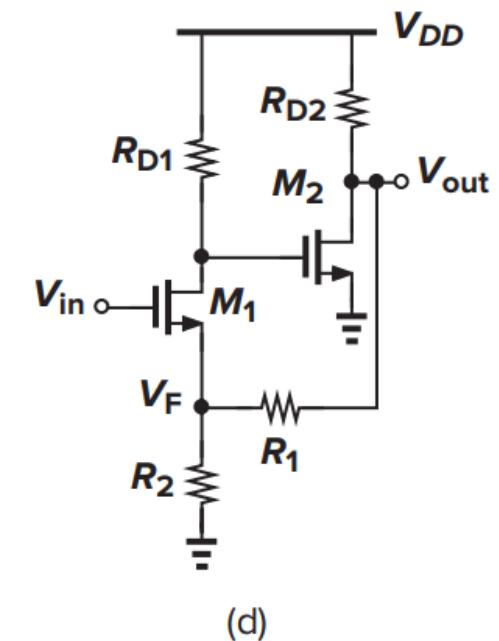
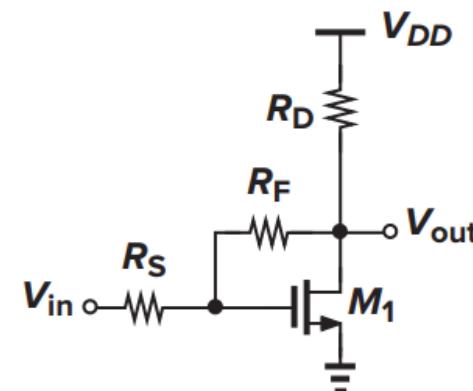
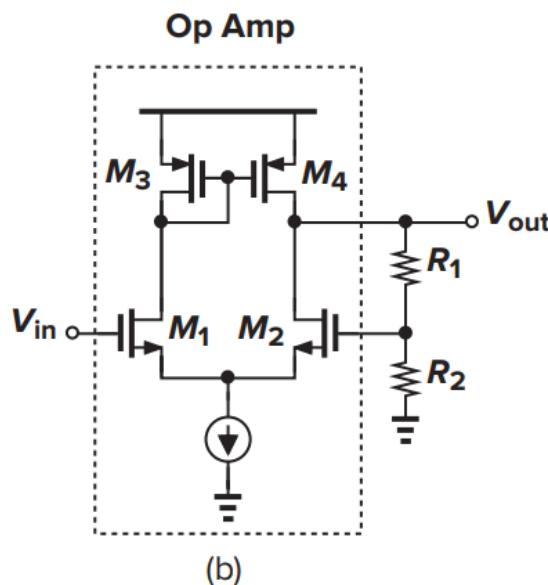
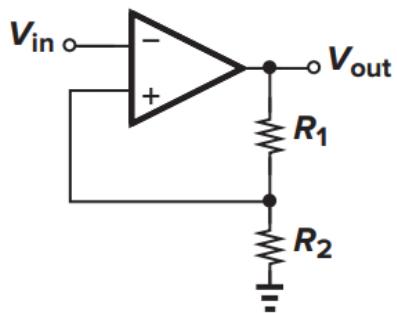
- 基本概念
- 反馈结构
- 负载影响分析

负载影响分析

- 负载影响分析难点
- 线性双端口模型
- 双端口模型分析方法

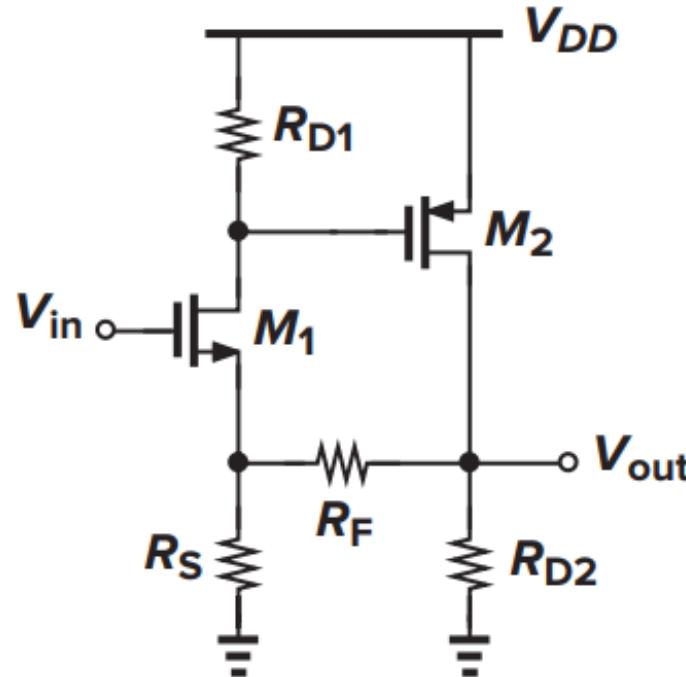
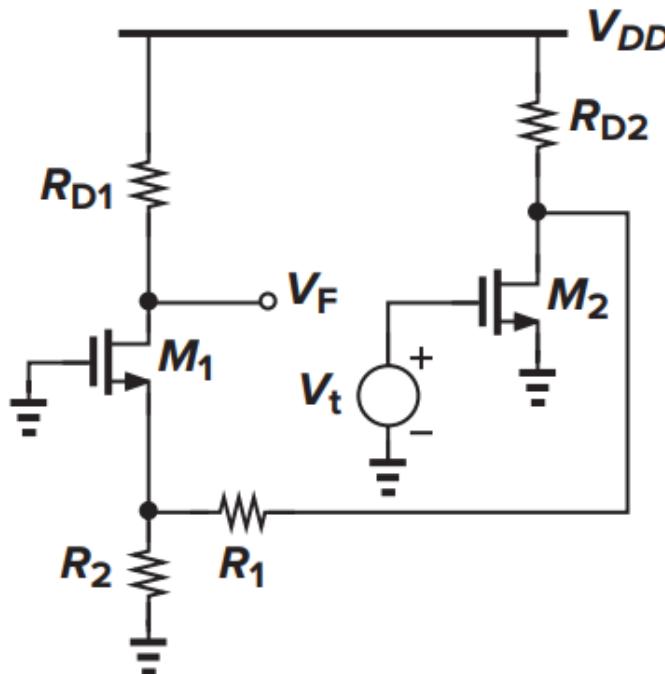
负载影响分析难点-1

- 反馈网络对前向放大电路的负载



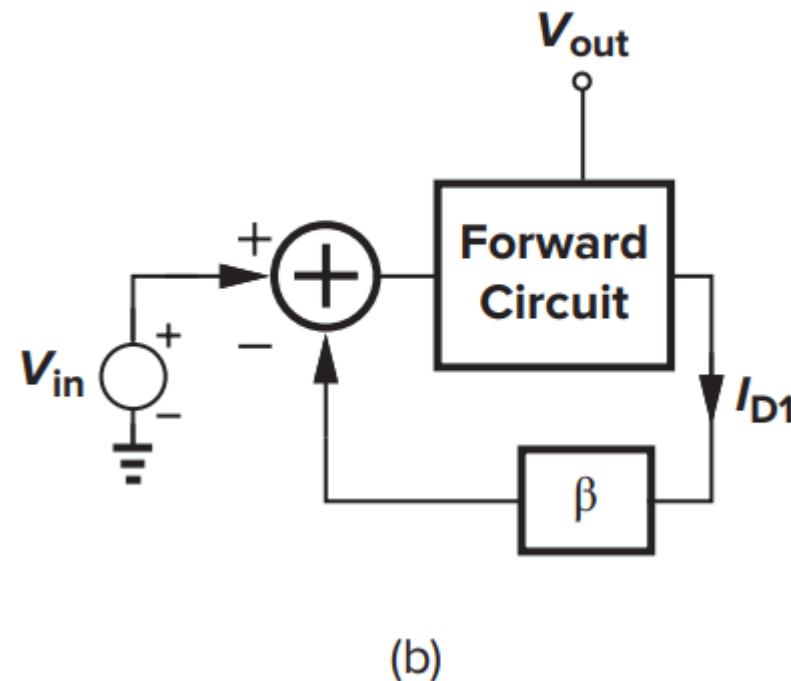
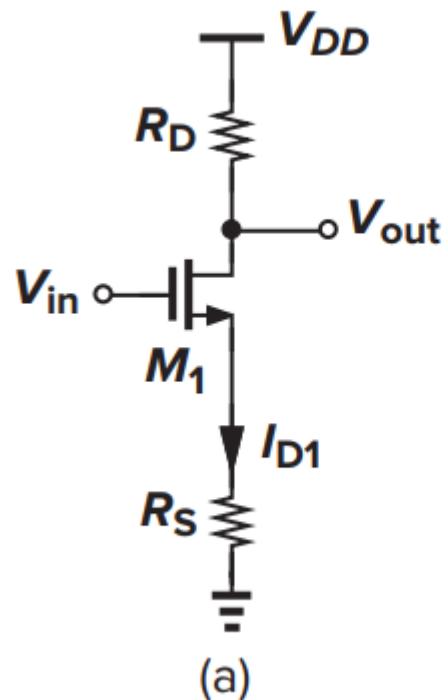
负载影响分析难点-2

- 前向放大电路和反馈电路难以分开



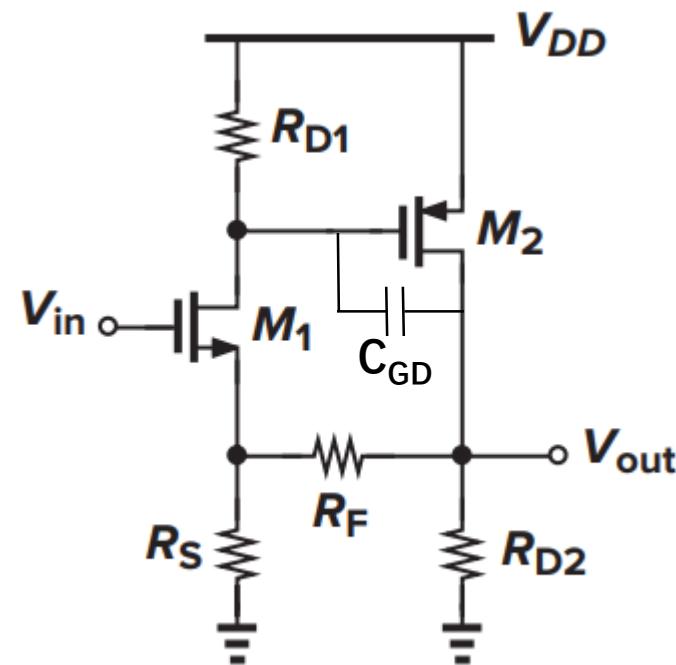
负载影响分析难点-3

- 电路无法分解成4种规范电路



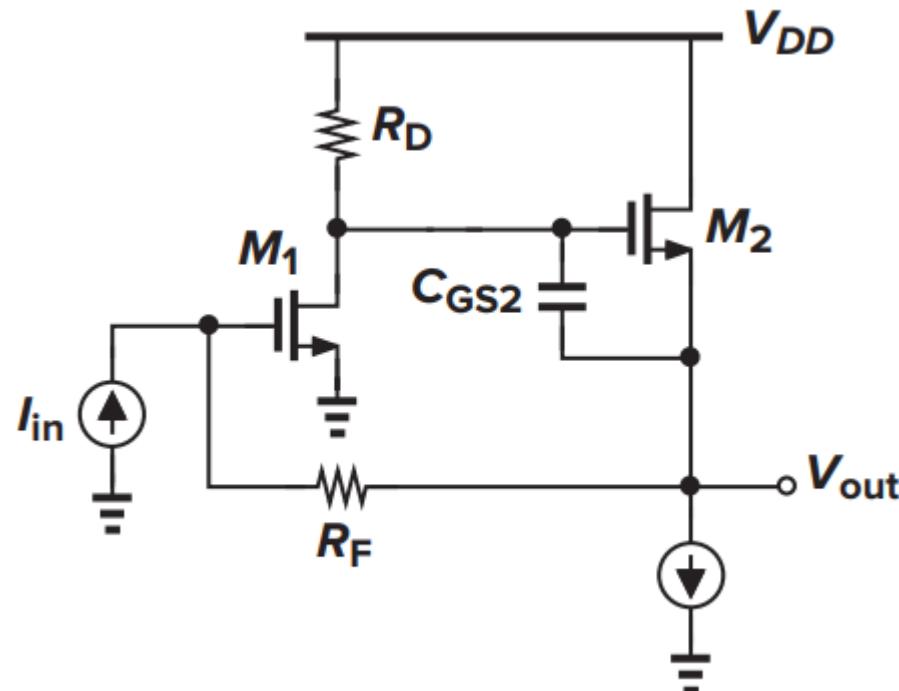
负载影响分析难点-4

- 多路径传输



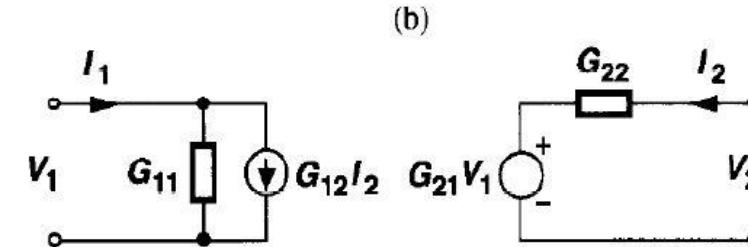
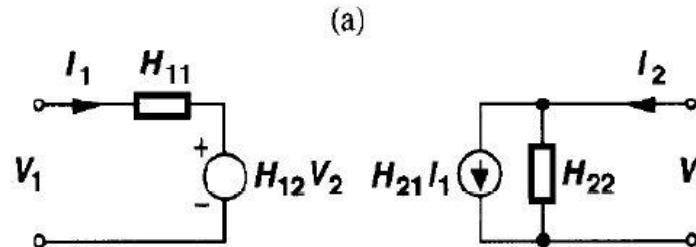
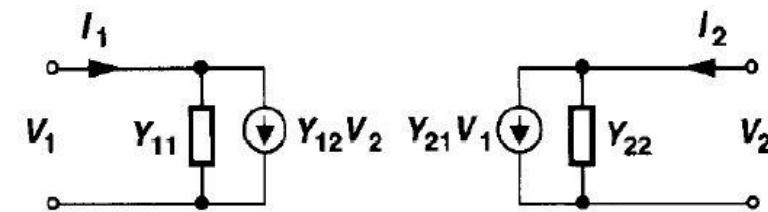
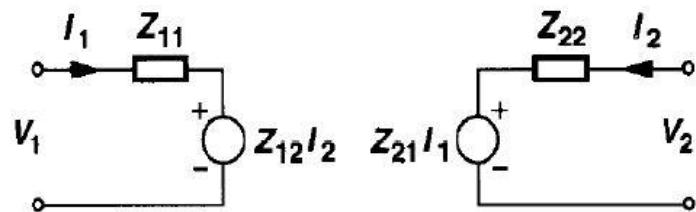
负载影响分析难点-5

- 多种反馈机制



线性双端口网络模型

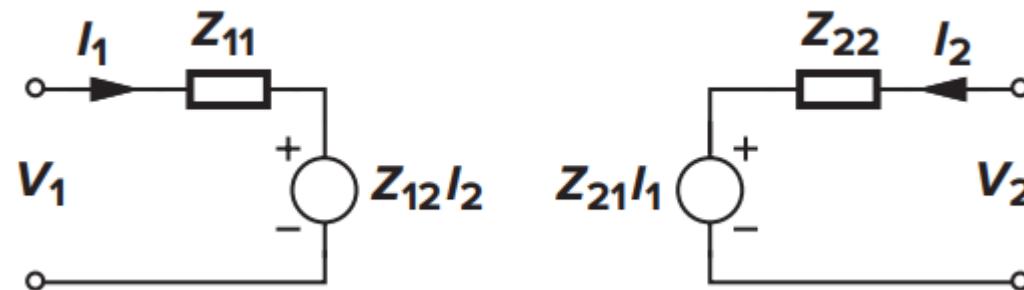
- 模型



- a. Z模型
- b. Y模型
- c. H模型
- d. G模型

线性双端口网络模型

- Z模型



$$V_1 = Z_{11}I_1 + Z_{12}I_2$$

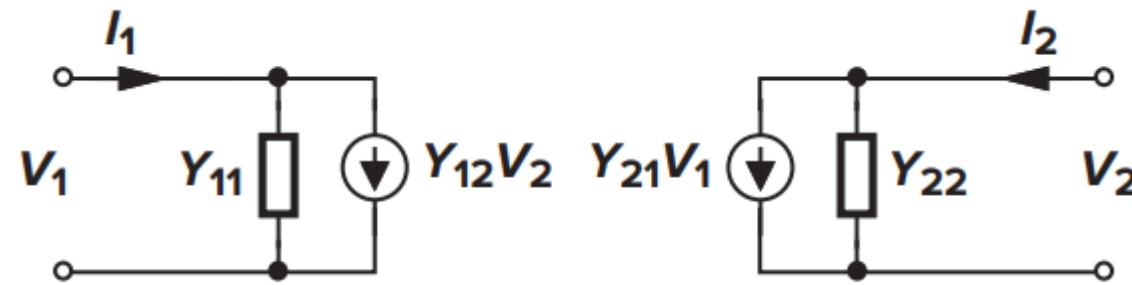
$$V_2 = Z_{21}I_1 + Z_{22}I_2$$

$Z_{21}I_1$: 反馈信号; I_1 : 检测信号

电流-电压反馈 (串联-串联反馈)

线性双端口网络模型

- Y模型



$$I_1 = Y_{11}V_1 + Y_{12}V_2$$

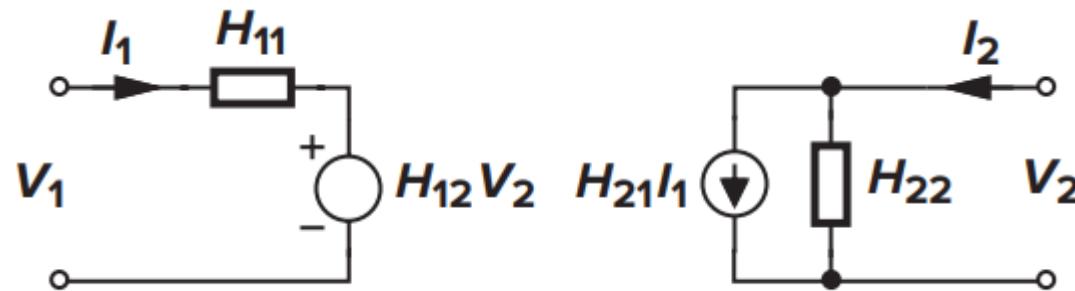
$$I_2 = Y_{21}V_1 + Y_{22}V_2$$

$Y_{21}V_1$: 反馈信号; V_1 : 检测信号

电压-电流反馈; 并联-并联反馈

线性双端口网络模型

- H模型



$$V_1 = H_{11}I_1 + H_{12}V_2$$

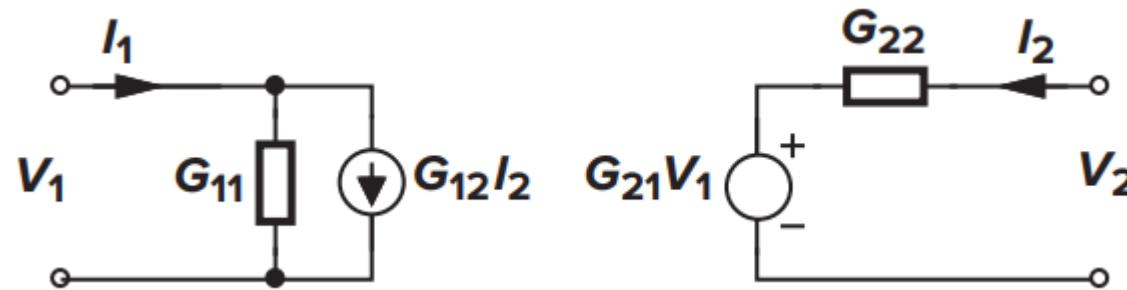
$$I_2 = H_{21}I_1 + H_{22}V_2$$

$H_{21}I_1$: 反馈信号; I_1 : 检测信号

电流-电流; 并联-串联反馈

线性双端口网络模型

- G模型



$$I_1 = G_{11}V_1 + G_{12}I_2$$

$$V_2 = G_{21}V_1 + G_{22}I_2$$

$G_{21}V_1$: 反馈信号; V_1 : 检测信号

电压-电压; 串联-并联反馈

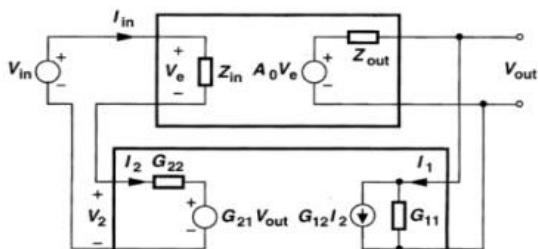
线性双端口网络模型

- 模型小结

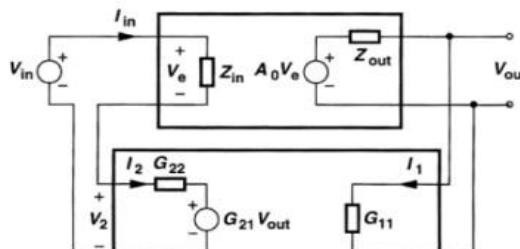
反馈网络类型	描述	对应模型
电压-电压	$V_2 = G_{21}V_1 + G_{22}I_2$	G模型
电流-电压	$V_2 = Z_{21}I_1 + Z_{22}I_2$	Z模型
电压-电流	$I_2 = Y_{21}V_1 + Y_{22}V_2$	Y模型
电流-电流	$I_2 = H_{21}I_1 + H_{22}V_2$	H模型

双端口模型分析方法

- 电压-电压反馈



(a)



(b)

采用不同模型表示反馈网络的电压-电压反馈电路

(a) G模型; (b) 简化的G模型

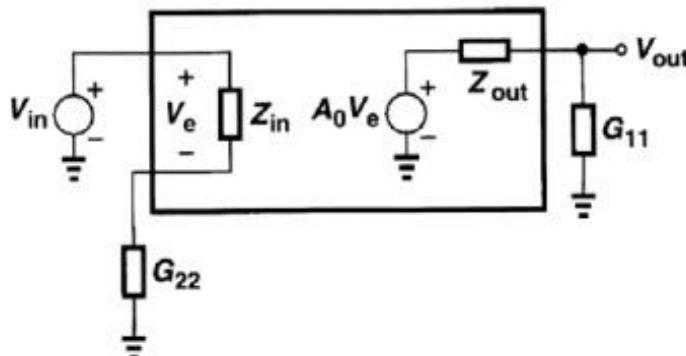
$$A_{0,closed} = \frac{V_{out}}{V_{in}}$$
$$= \frac{A_0 \frac{Z_{in}}{Z_{in} + G_{22}} \frac{G_{11}^{-1}}{G_{11}^{-1} + Z_{out}}}{1 + \frac{Z_{in}}{Z_{in} + G_{22}} \frac{G_{11}^{-1}}{G_{11}^{-1} + Z_{out}} G_{21} A_0}$$

$$\text{If } \frac{I_1}{V_1} = \infty, \quad G_{22} = 0, \quad A_{0,closed} = \frac{A_0}{1 + G_{21} A_0}$$

$$A_{v,open} = \frac{Z_{in}}{Z_{in} + G_{22}} \frac{G_{11}^{-1}}{G_{11}^{-1} + Z_{out}} A_0$$

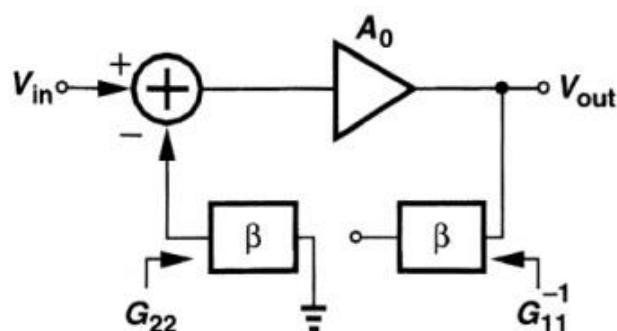
双端口模型分析方法

- G模型分析方法



$$A_{v,open} = \frac{Z_{in}}{Z_{in} + G_{22}} \frac{G_{11}^{-1}}{G_{11}^{-1} + Z_{out}} A_0$$

$$I_1 = G_{11} V_1 + G_{12} I_2$$



$$V_2 = G_{21} V_1 + G_{22} I_2$$

$$G_{11} = \left. \frac{I_1}{V_1} \right|_{I_2=0} \quad G_{22} = \left. \frac{V_2}{I_2} \right|_{V_1=0}$$

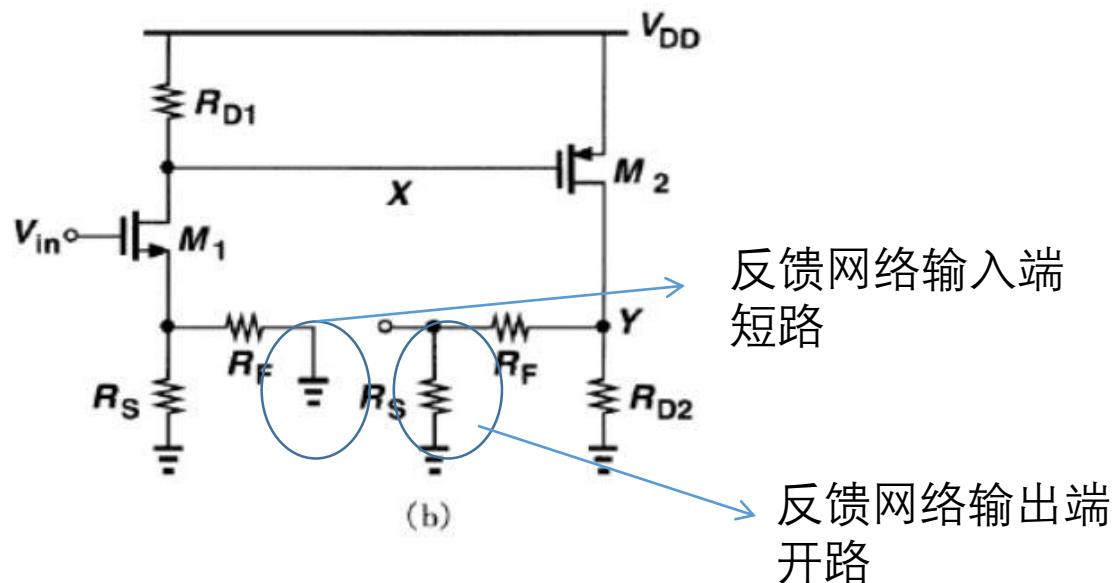
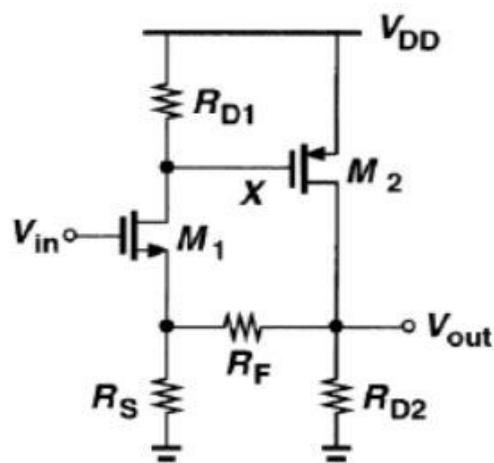
电压-电压反馈的负载计算

反馈网络输出端开路

反馈网络输入端短路

双端口模型分析方法

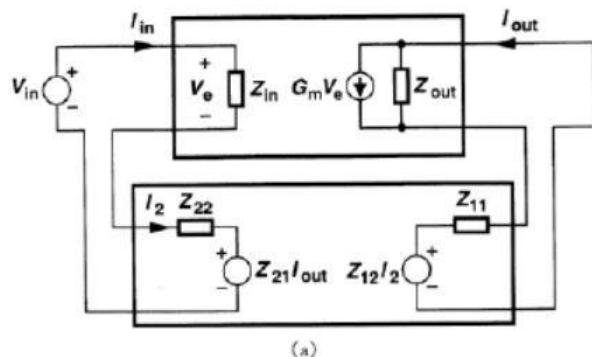
- 电压-电压反馈分析（例）



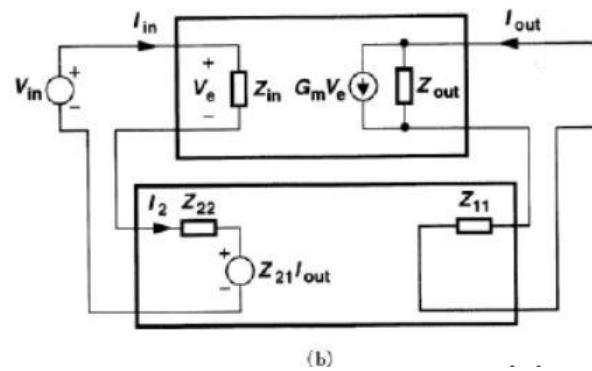
$$A_{v,open} = \frac{V_Y}{V_{in}} = \frac{-R_{D1}}{R_F \parallel R_S + 1/g_{m1}} \{-g_{m2}[R_{D2} \parallel (R_F + R_S)]\}$$

双端口模型分析方法

- 电流-电压反馈



(a)



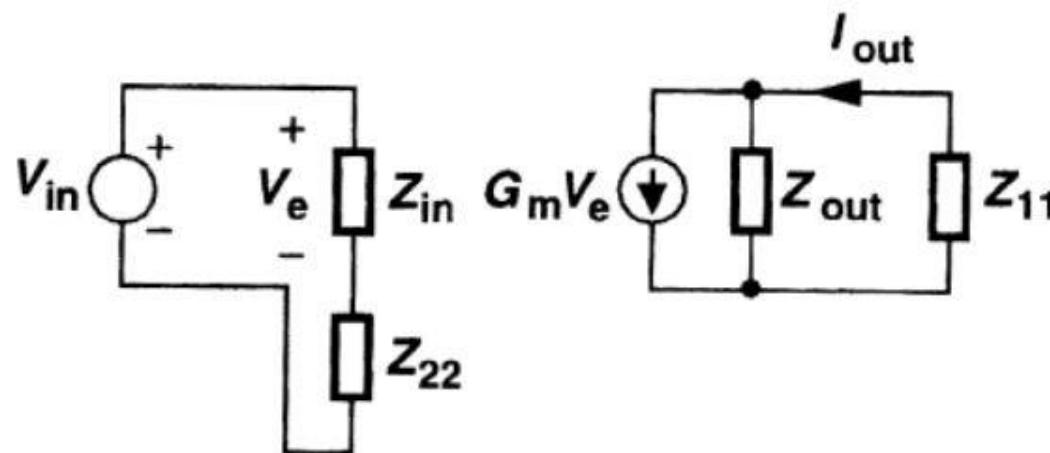
(b)

(a) Z模型; (b) 简化的Z模型

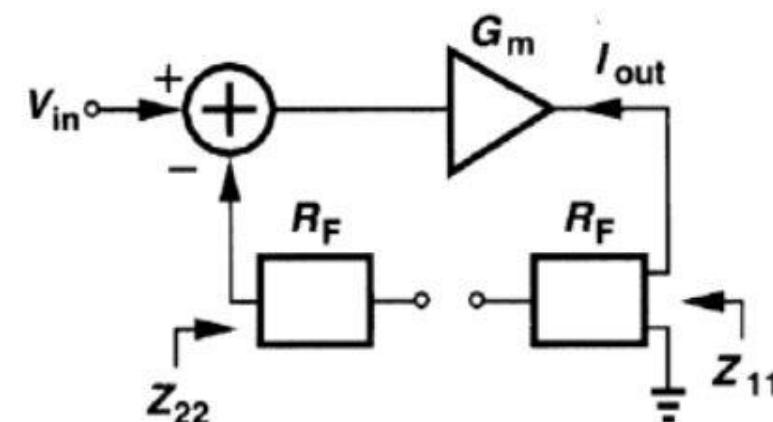
$$\frac{I_{out}}{V_{in}} = \frac{\frac{Z_{in}}{Z_{in} + Z_{22}} \frac{Z_{out}}{Z_{out} + Z_{11}} G_m}{1 + \frac{Z_{in}}{Z_{in} + Z_{22}} \frac{Z_{out}}{Z_{out} + Z_{11}} G_m Z_{21}}$$

双端口模型分析方法

- 电流-电压反馈分析原理 (Z模型)



有反馈网络适当负载的电流-电压反馈电路

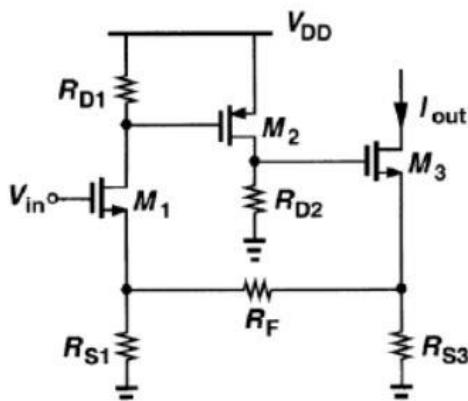


断开电流-电压反馈环路的原理图

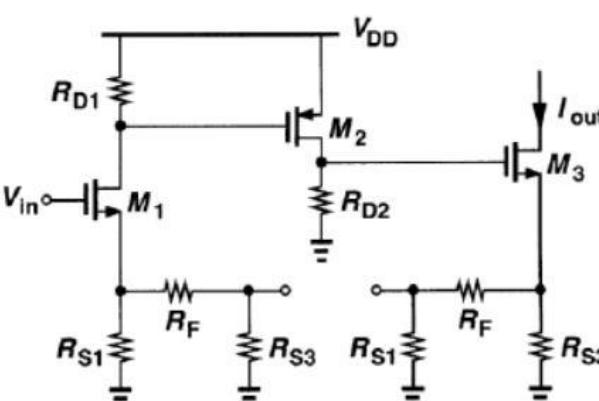
$$G_{m,open} = \frac{Z_{in}}{Z_{in} + Z_{22}} \frac{Z_{out}}{Z_{out} + Z_{11}} G_m$$

双端口模型分析方法

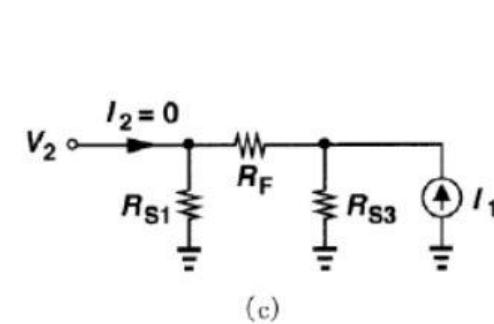
- 电流-电压反馈分析（例）



(a)



(b)



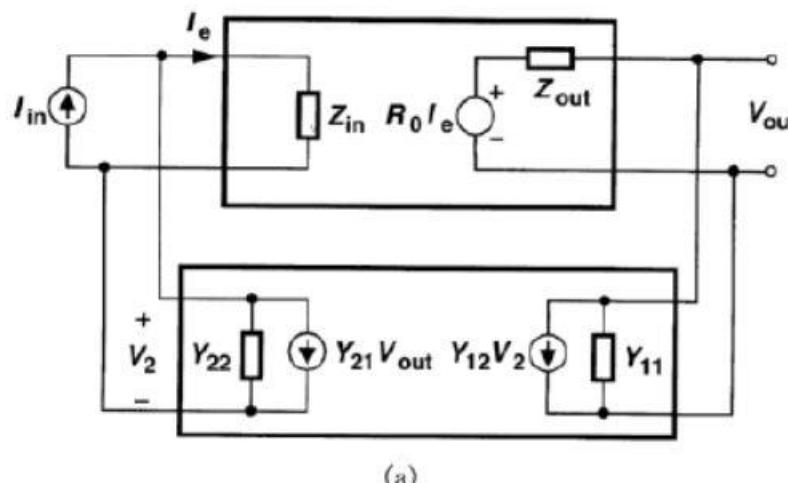
(c)

$$G_{m,open} = \frac{-R_{D1}}{R_{S1} \parallel (R_F + R_{S3}) + 1/g_{m1}} \cdot \frac{-g_{m2}R_{D2}}{R_{S3} \parallel (R_F + R_{S1}) + 1/g_{m3}}$$

$$Z_{21} = \frac{R_{S3}}{R_{S3} + R_{S1} + R_F} R_{S1}$$

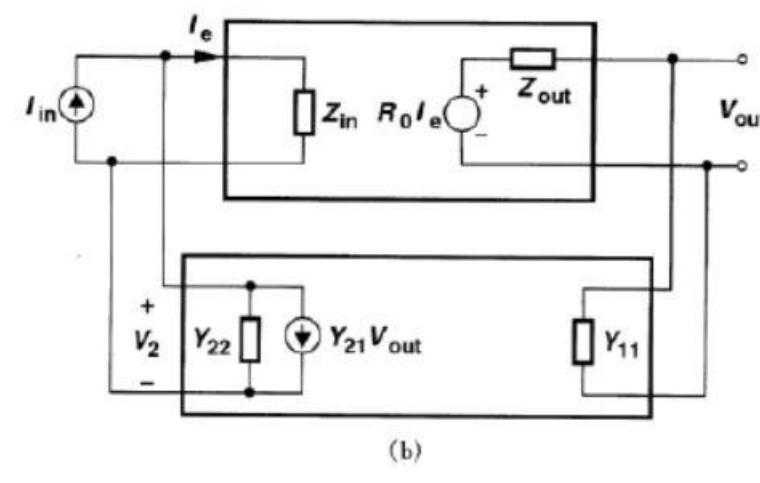
双端口模型分析方法

- 电压-电流反馈中的负载



(a)

Y模型



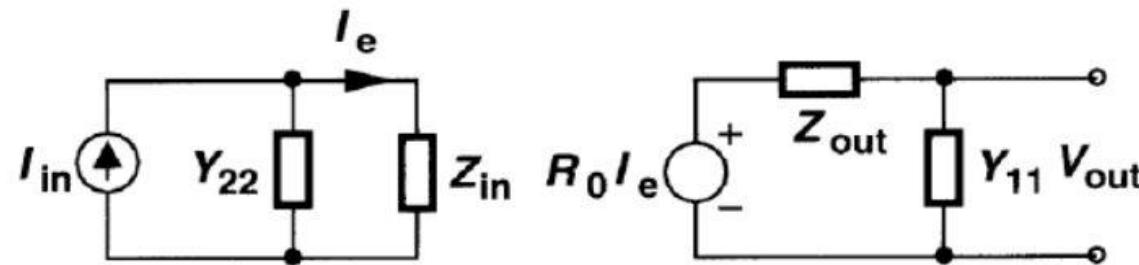
(b)

简化的Y模型

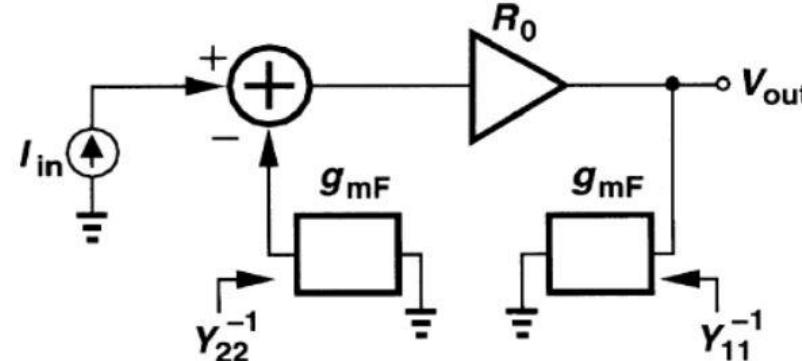
$$R_{0,open} = \frac{Y_{22}^{-1}}{Y_{22}^{-1} + Z_{in}} \frac{Y_{11}^{-1}}{Y_{11}^{-1} + Z_{out}} R_0$$

双端口模型分析方法

- 电压-电流反馈中的负载分析原理 (Y模型)



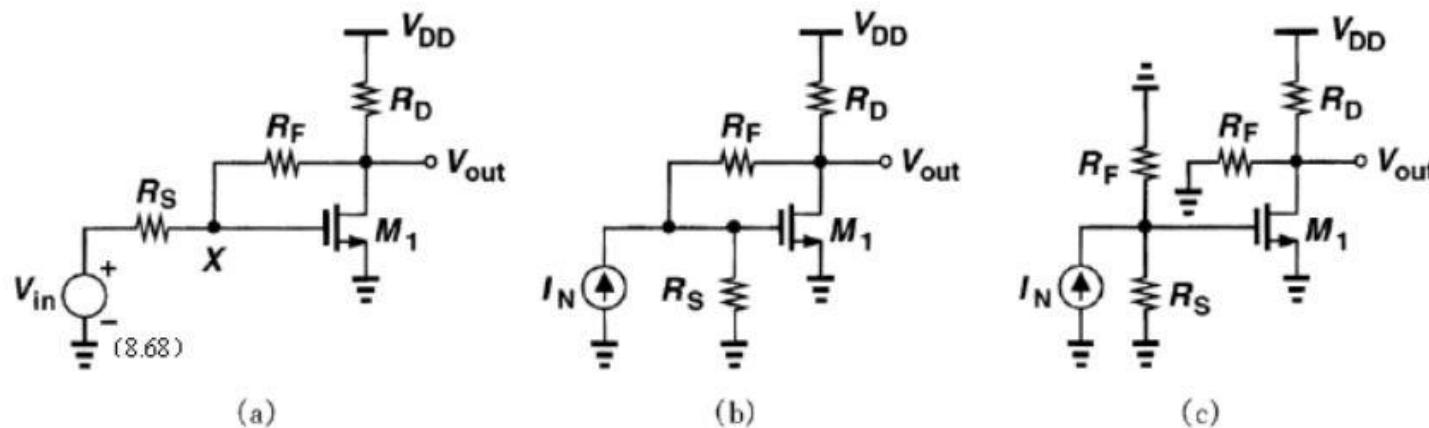
有反馈网络的适当负载的电压-电流反馈电路



断开电压-电流反馈环路的原理图

双端口模型分析方法

- 电压-电流反馈中的负载分析（例）

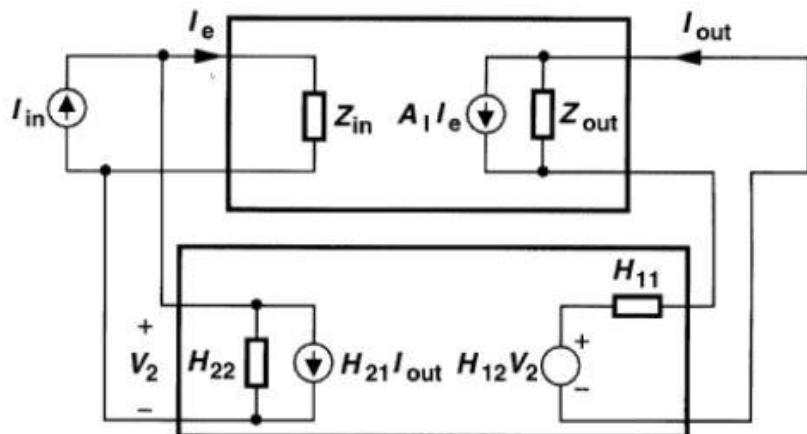


$$R_{0,open} = -(R_S \parallel R_F)g_m(R_F \parallel R_D)$$

$$\frac{V_{out}}{V_{in}} = \frac{1}{R_S} \cdot \frac{-(R_S \parallel R_F)g_m(R_F \parallel R_D)}{1 + g_m(R_F \parallel R_D)R_S/(R_S + R_F)}$$

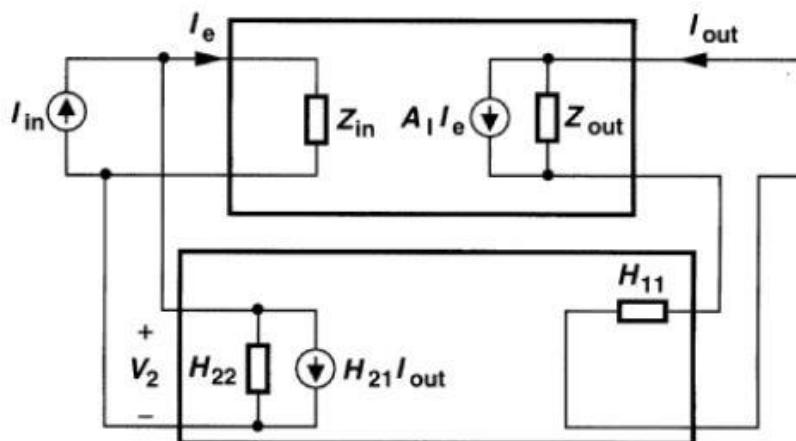
双端口模型分析方法

- 电流-电流反馈的负载



(a)

H模型



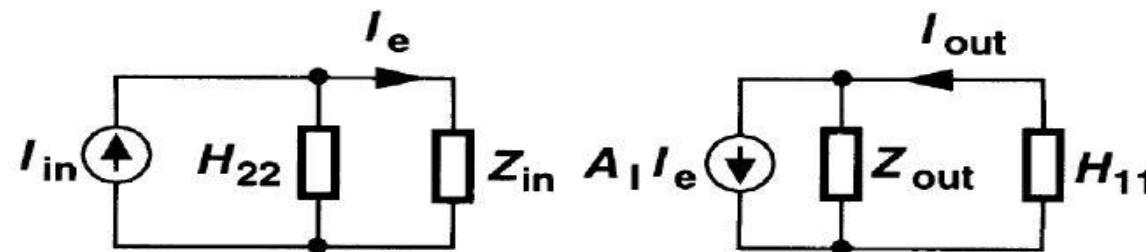
(b)

简化的H模型

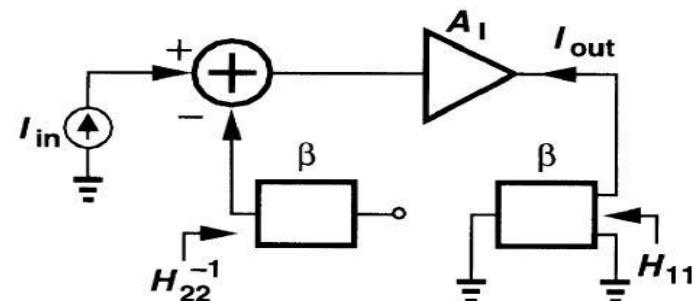
$$\frac{I_{out}}{I_{in}} = \frac{H_{22}^{-1}}{H_{22}^{-1} + Z_{in}} \frac{Z_{out}}{H_{11} + Z_{out}} A_I$$

双端口模型分析方法

- 电流-电流反馈的负载分析原理



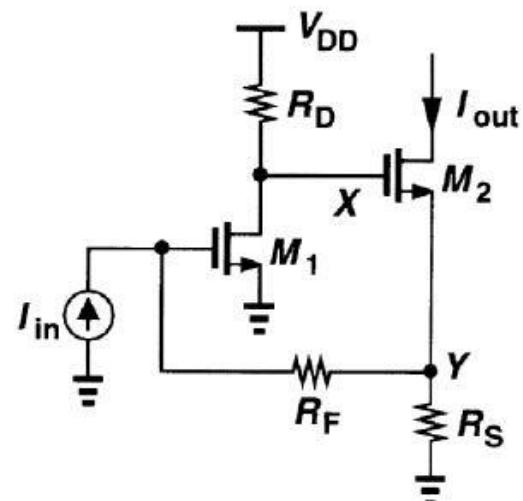
反馈网络中有适当负载的电流-电流反馈



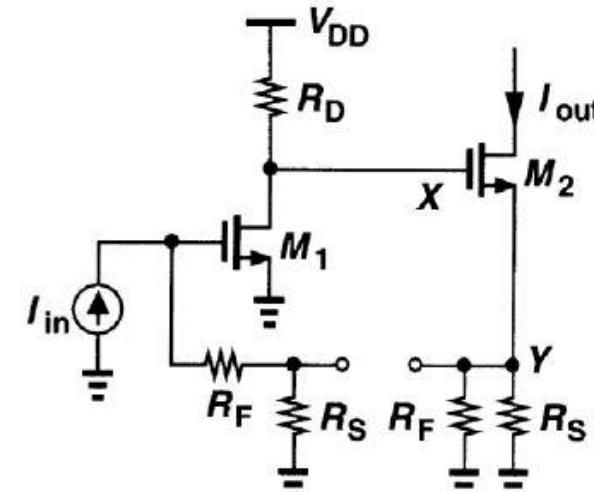
电流-电流反馈中计入负载影响的原理图

双端口模型分析方法

- 电流-电流反馈的负载分析（例）



(a)

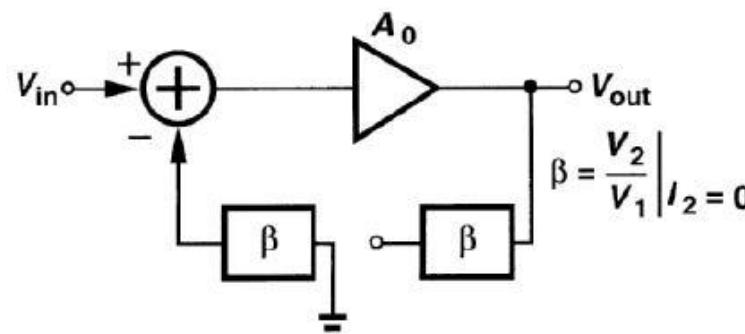


(b)

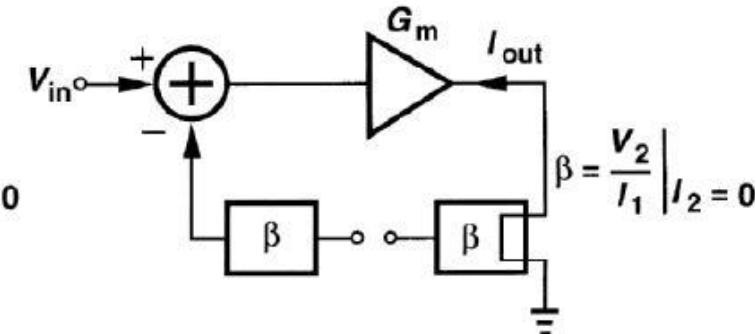
$$A_{I,open} = -(R_F + R_S)g_{m1}R_D \frac{1}{R_S \parallel R_F + 1/g_{m2}}$$

双端口模型分析方法

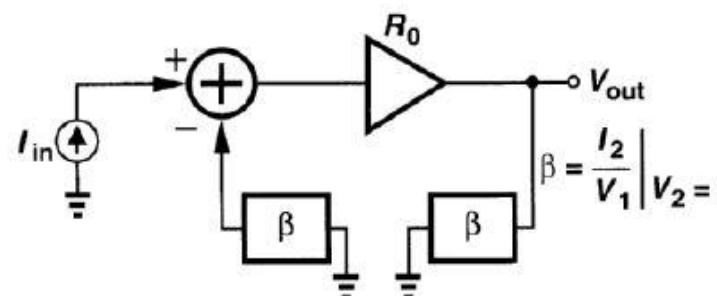
- 小结



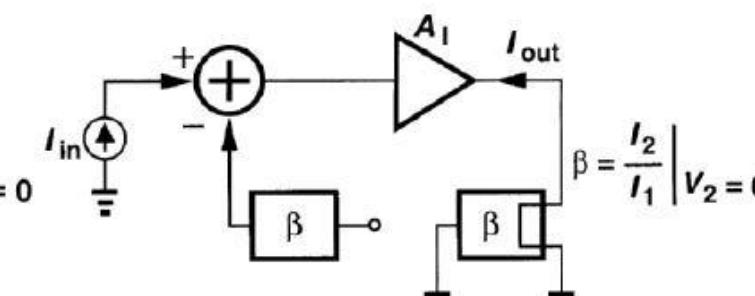
(a)



(b)



(c)



(d)

双端口模型分析方法

- 识别反馈类型和结构；
- 断开环路；
- 计算开环增益AOL和开环输入和输出阻抗；
- 确定反馈系数 β ，得出环路增益 βAOL ；
- 将开环的各个值通过比例因子 $(1 + \beta AOL)$ 的变化，计算闭环增益、输入和输出的阻抗；

作业

- 8.8, 8.11