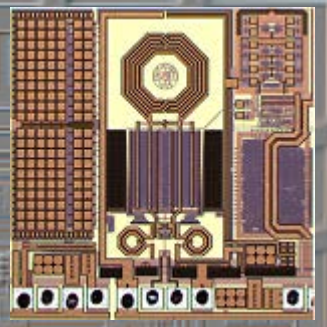

模拟集成电路设计原理

(Principle of Analog Integrated Circuit Design, INF0130025.02)

2014年12月11日

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http://rfic.fudan.edu.cn/Courses.htm

复旦大学/微电子学院/射频集成电路设计研究小组

反馈
跨阻放大器和电流放大器

目录

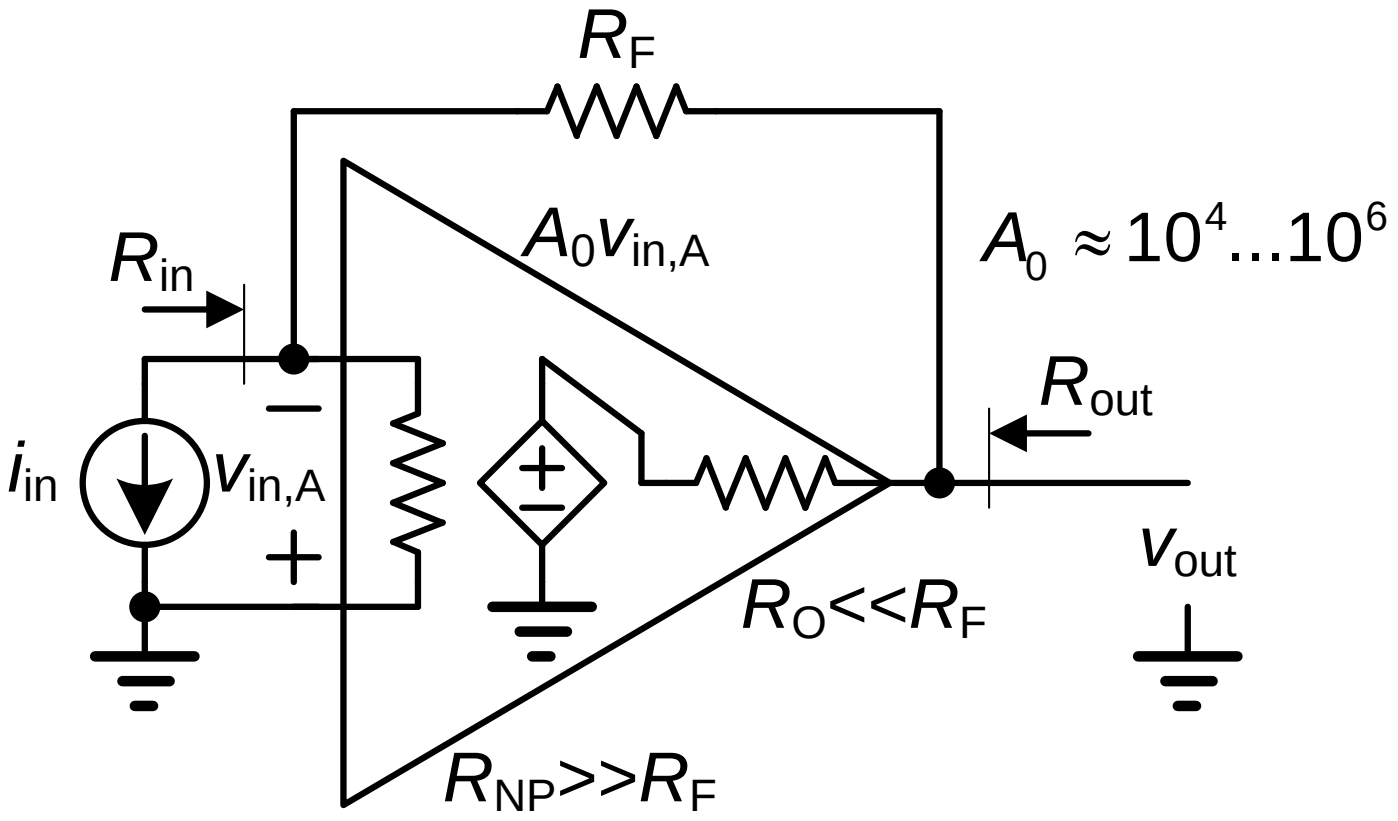
Ref.: W. Sansen : Analog Design Essentials, Springer 2006

输入和输出阻抗

$\frac{1}{H}=$	输出	并联	串联
输入		$R_{out}=\frac{R_{outOL}}{1+LG}$	$R_{out}=R_{outOL}(1+LG)$
并联	$R_{in}=\frac{R_{inOL}}{1+LG}$	$\frac{v_{out}}{i_{in}}=A_R$	$\frac{i_{out}}{i_{in}}=A_I$
串联 $R_{in}=R_{inOL}(1+LG)$		$\frac{v_{out}}{v_{in}}=A_V$	$\frac{i_{out}}{v_{in}}=A_G$

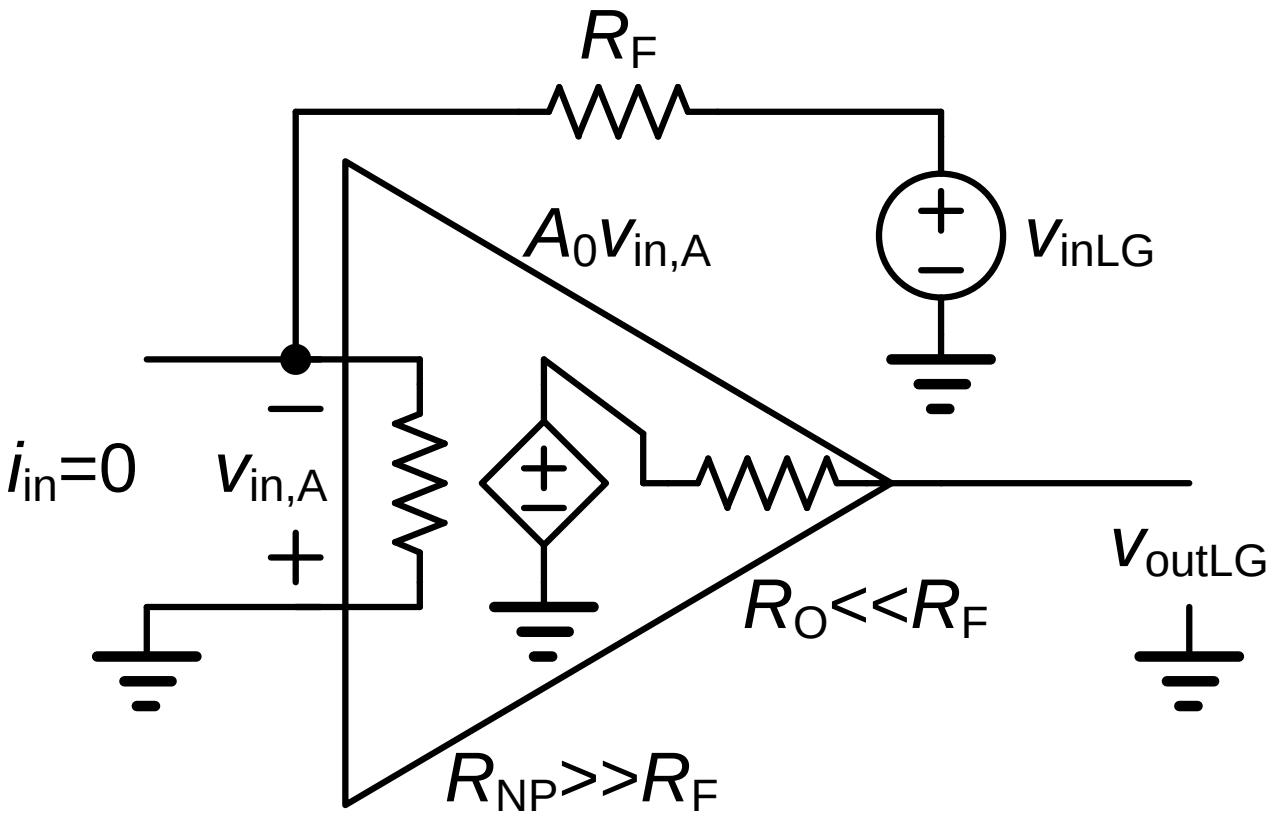
目录

并联-并联反馈结构



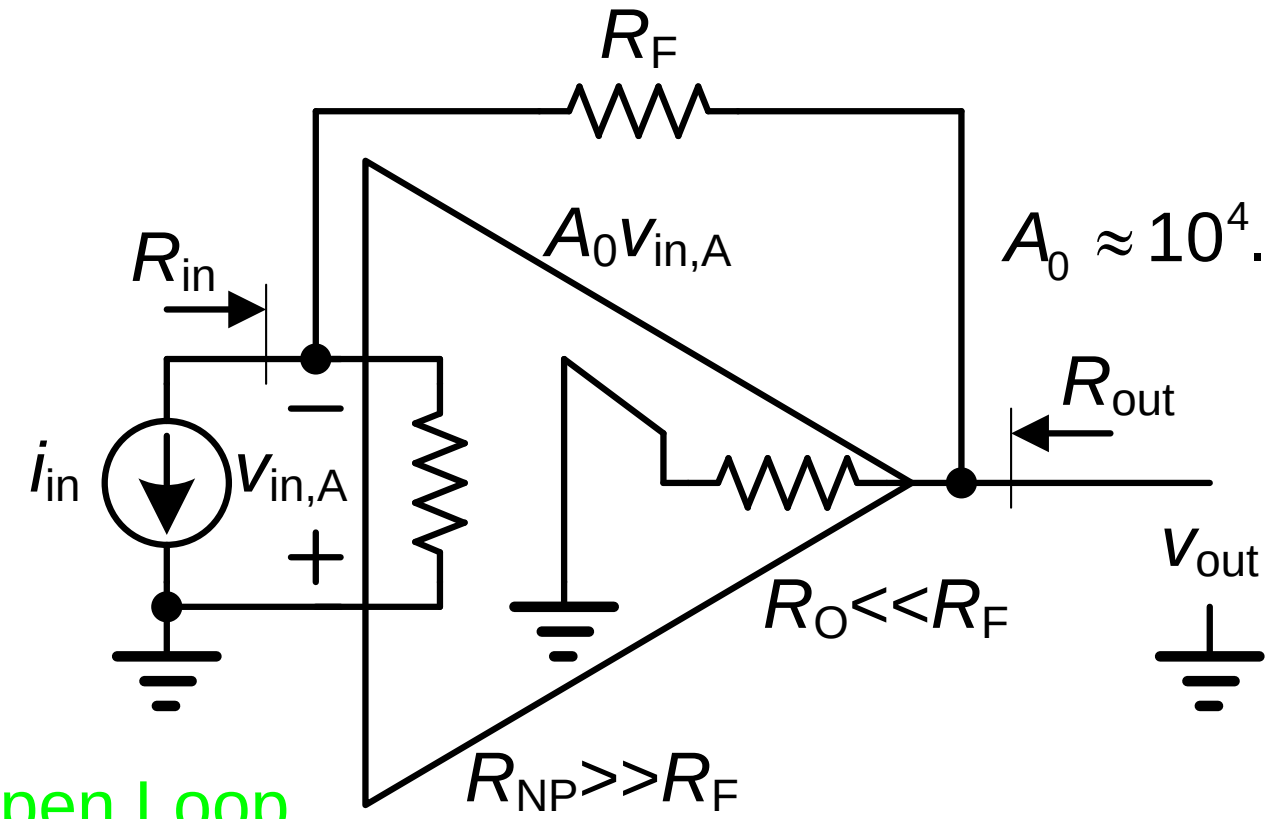
$$A_R = \frac{v_{out}}{i_{in}} = R_F \qquad R_{in} \approx 0 \qquad R_{out} \approx 0$$

并联-并联反馈：环路增益



$$LG = \frac{v_{outLG}}{v_{inLG}} \approx A_{VOL} \approx A_0 \approx 10^4 ... 10^6$$

并联-并联反馈：输入电阻

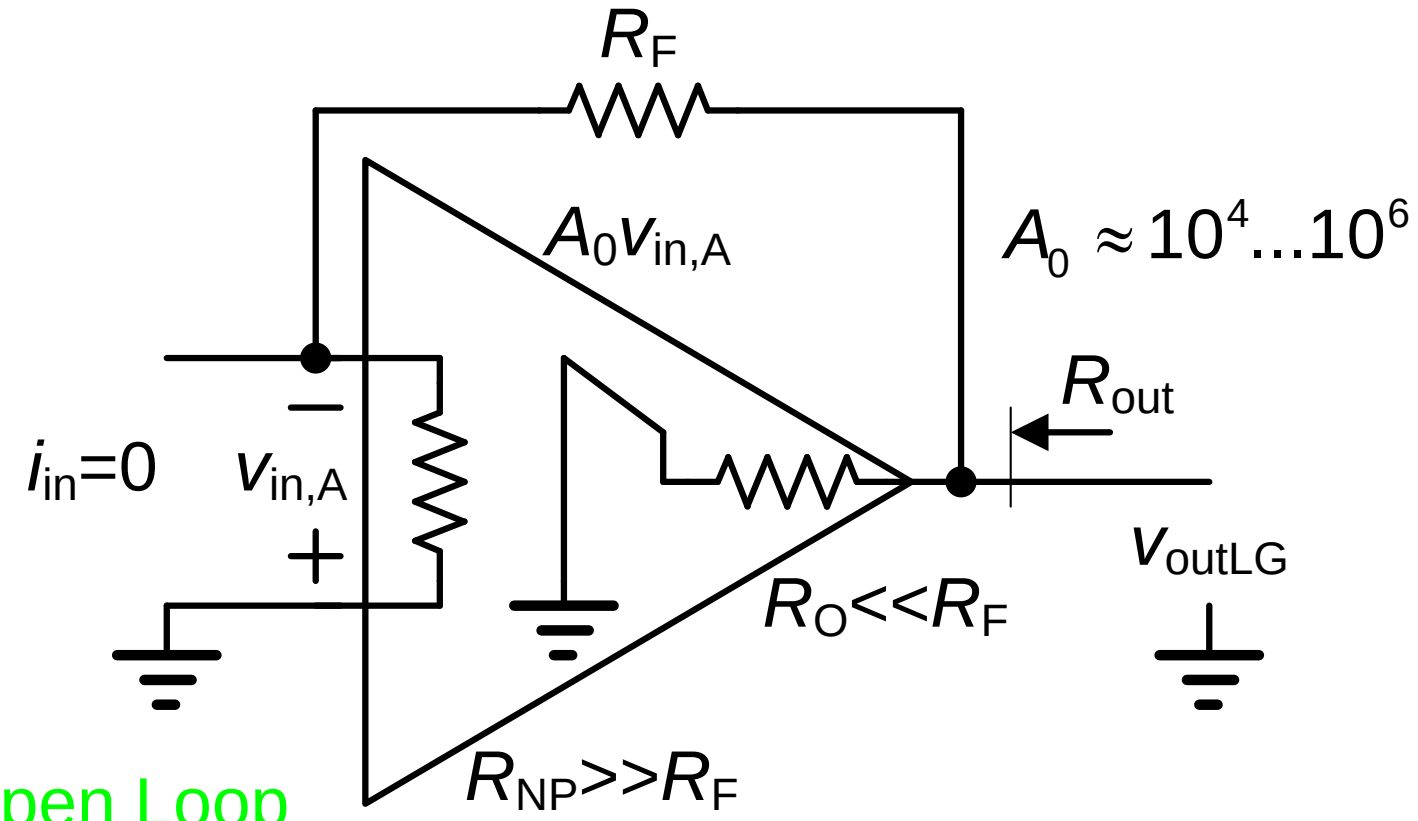


OL： Open Loop

$$R_{in} = \frac{v_{in}}{i_{in}} = \frac{R_{inOL}}{LG} \approx 0$$

$$R_{inOL} = R_{in}(A_V = 0) = R_{NP} // (R_F + R_O) \approx R_F$$

并联-并联反馈：输出电阻

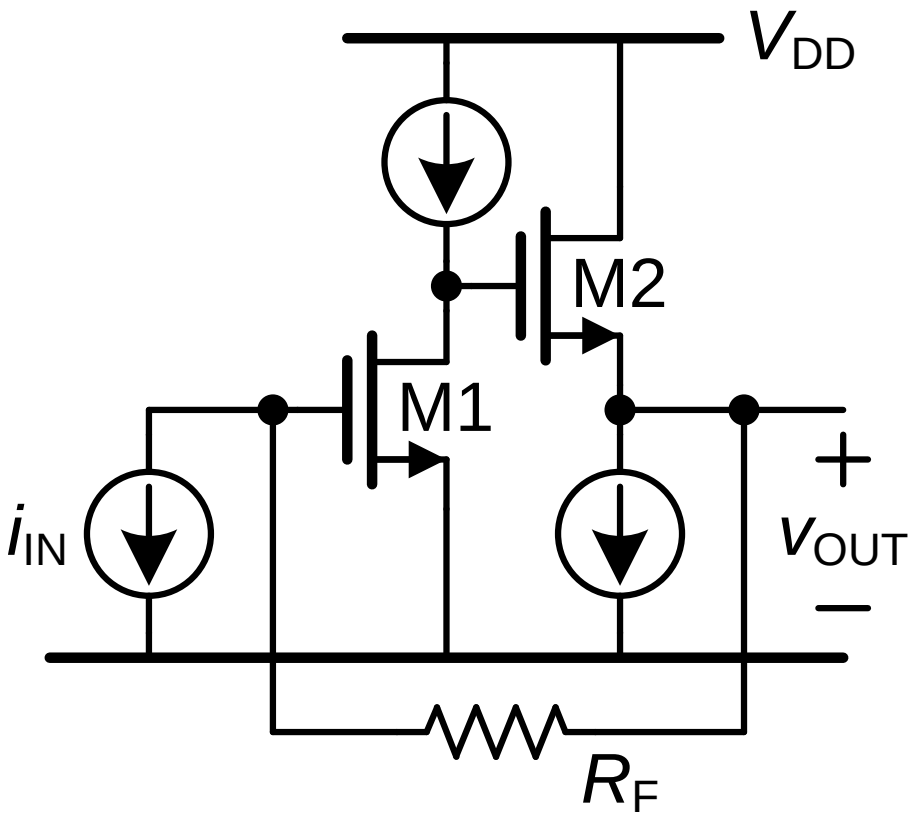


OL：Open Loop

$$R_{out} = \frac{R_{outOL}}{LG} \approx 0$$

$$R_{outOL} = R_{out}(A_V = 0) = R_O // (R_F + R_{NP}) \approx R_O$$

并联-并联反馈



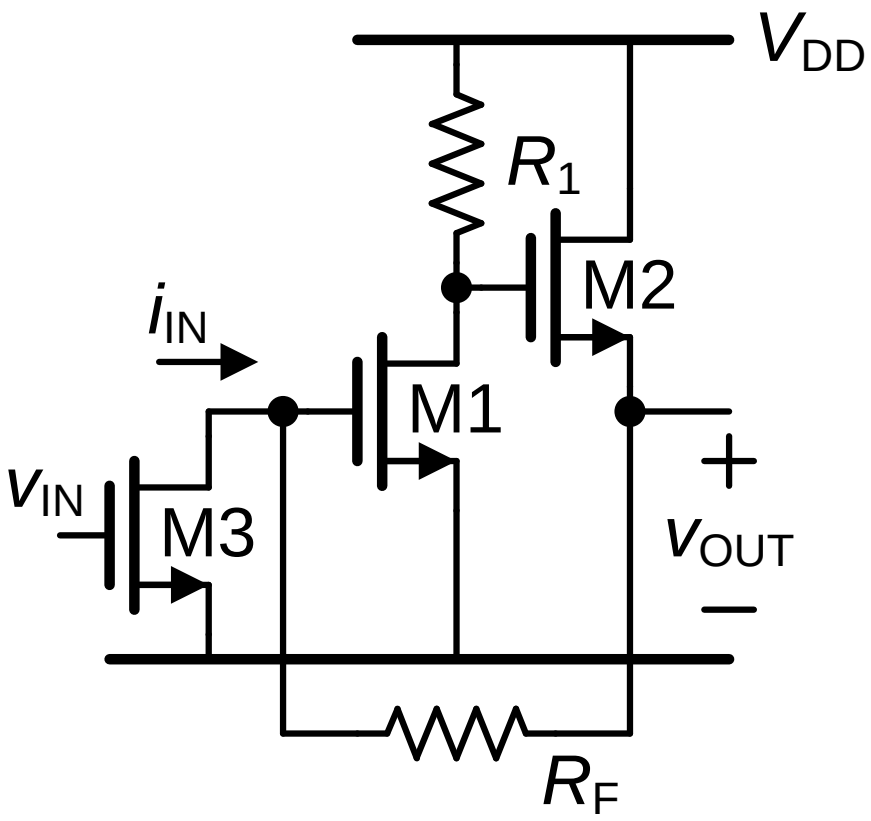
$$A_R = \frac{v_{out}}{i_{in}} = R_F$$

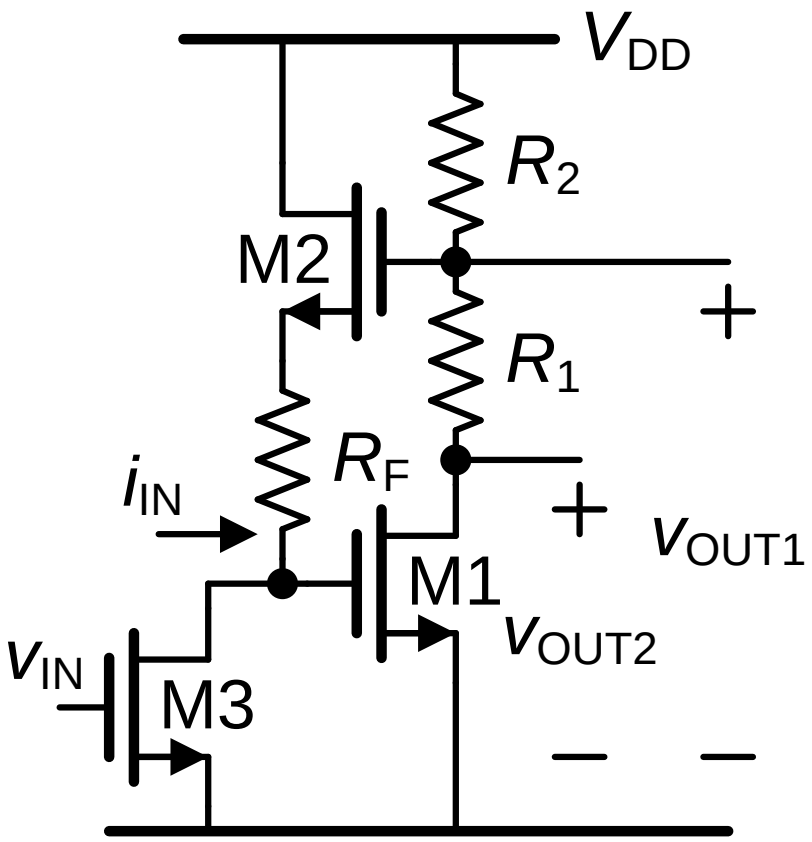
$$LG = g_{m1} r_{DS1}$$

$$R_{in} = \frac{R_F}{LG} \approx 0\ ?$$

$$R_{out} = \frac{1/g_{m2}}{LG} \approx 0$$

接电阻的并联-并联反馈



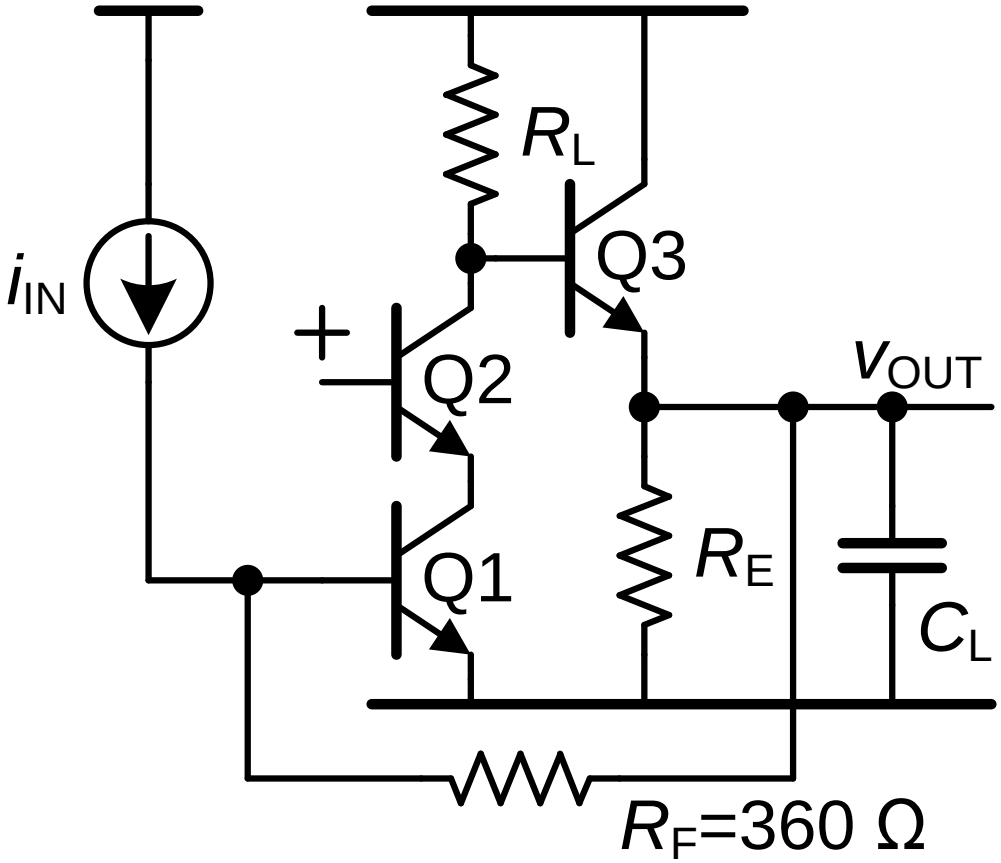


$$A_R = \frac{v_{out}}{i_{in}} = R_F$$

$$A_{R1} = R_F \quad A_{R2} = R_F \frac{R_1 + R_2}{R_2}$$

Ref.: Cherry, Proc. IEE, Feb.63, 375-389; Holdenried, JSSC Nov.04, 1959-1967

接电压放大器的电流检测器



$$f_T = 40\ \text{GHz}$$

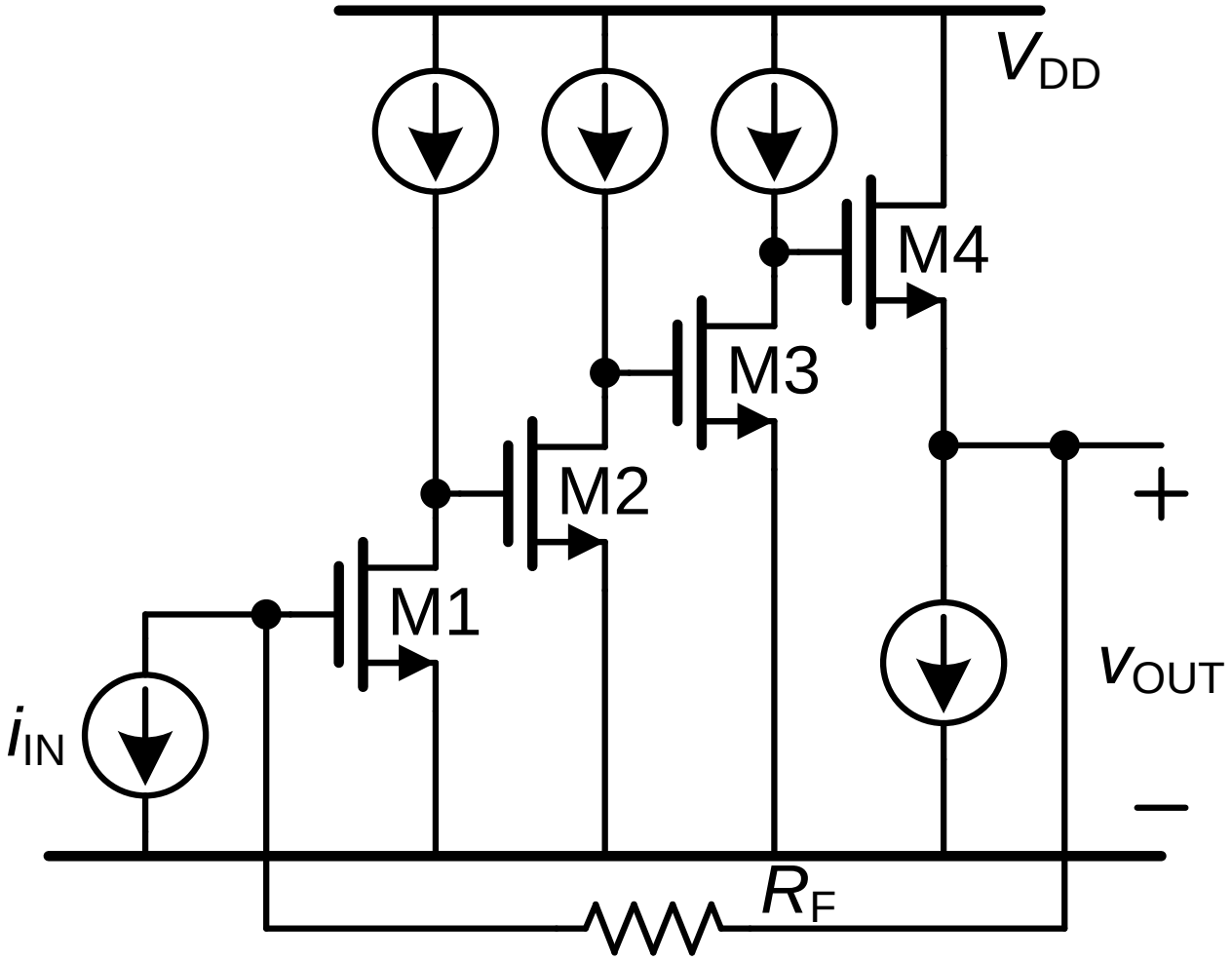
$$r_B = 20\ \Omega$$

$$BW = 10\ \text{GHz}$$

$$I_{TOT} = 10\ \text{mA}$$

Ref.: Baureis, JSSC June 1993, 701-706

并联-并联反馈



$$A_R = R_F$$

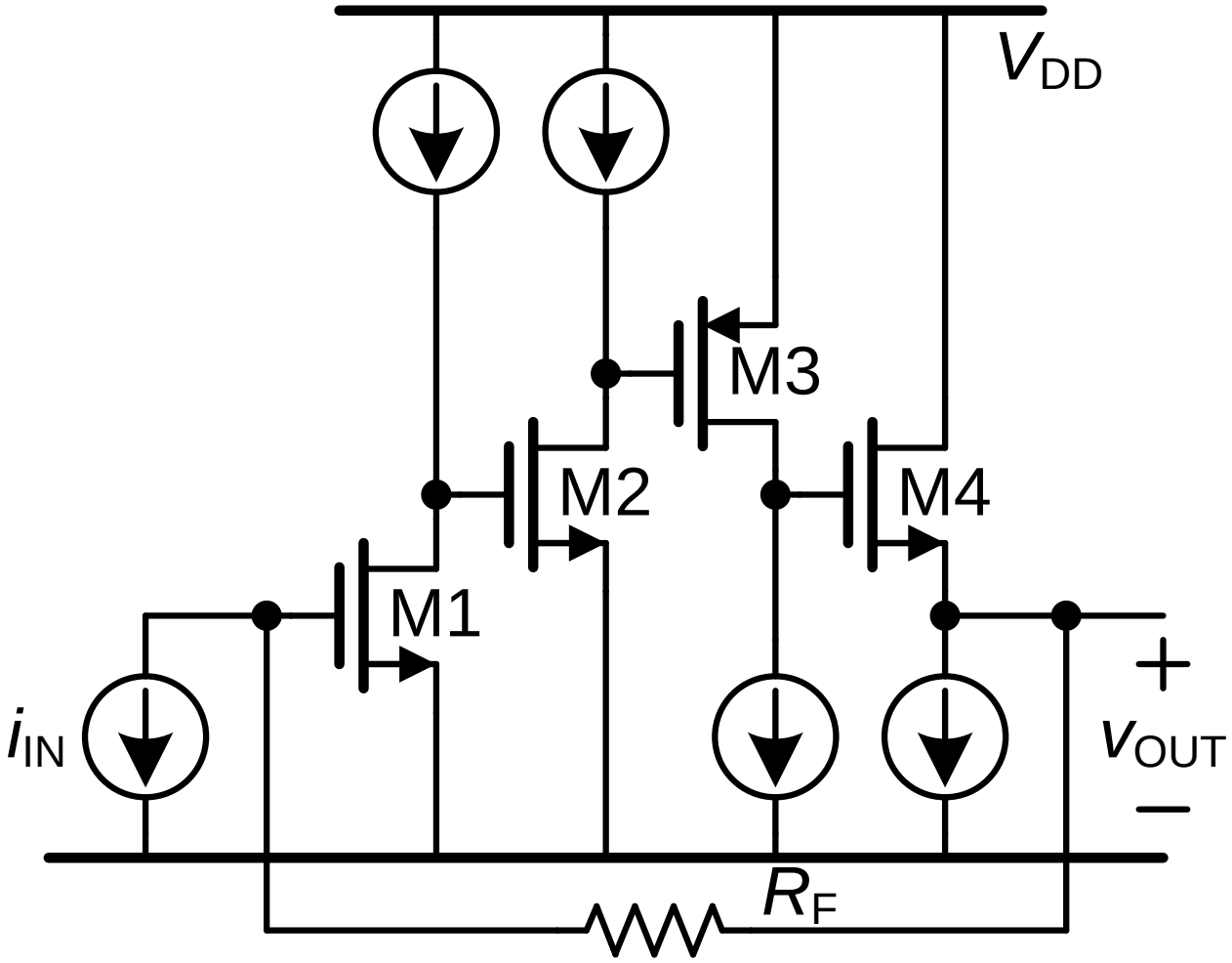
$$LG = A_{V1}A_{V2}A_{V3}$$

$$A_{Vi} = g_{mi}r_{DSi}$$

$$R_{in} = \frac{R_F}{LG} \approx 0$$

$$R_{out} = \frac{1/g_{m4}}{LG} \approx 0$$

并联-并联反馈：合理偏置



$$A_R = R_F$$

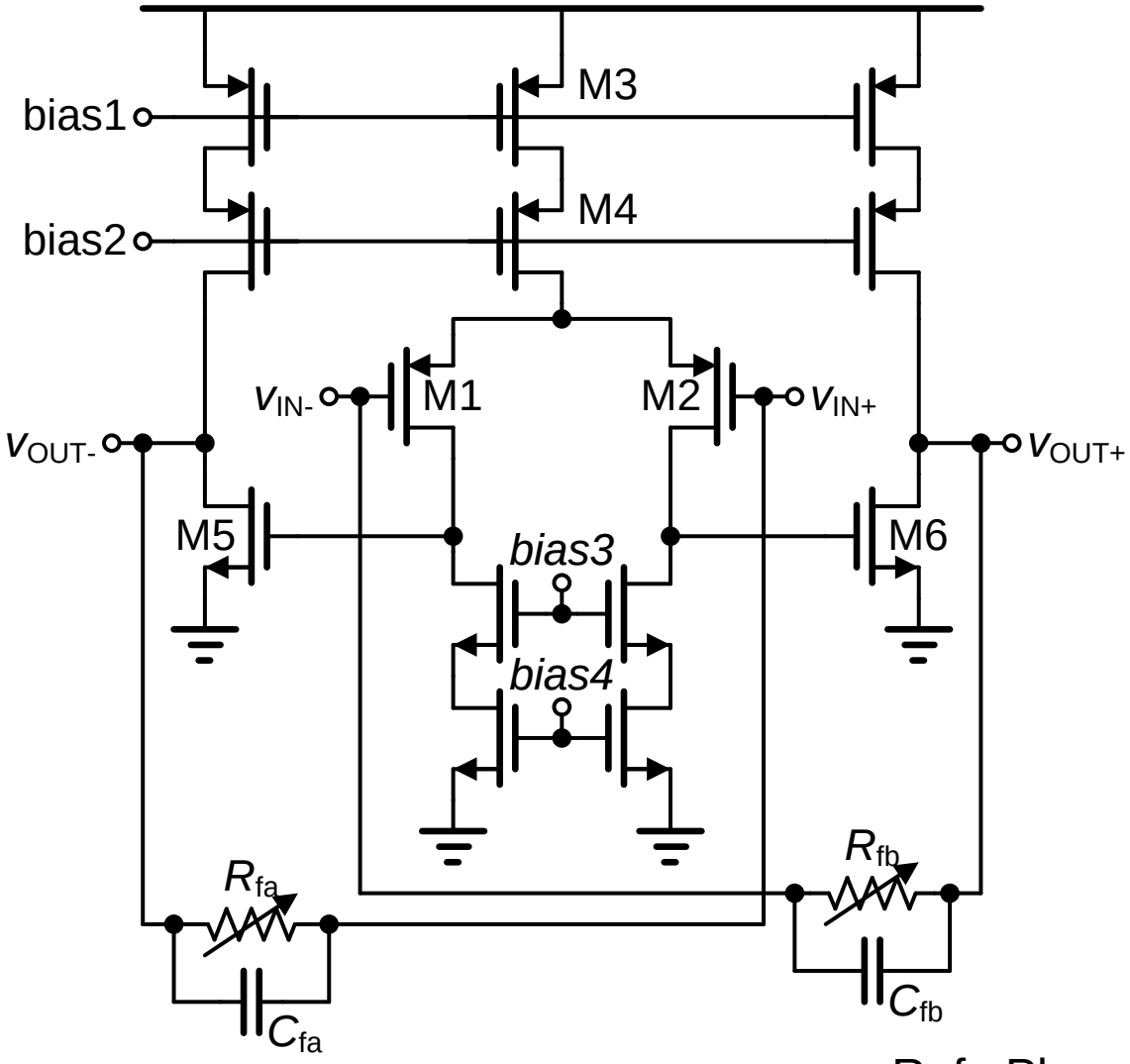
$$LG = A_{V1}A_{V2}A_{V3}$$

$$A_{Vi} = g_{mi}r_{DSi}$$

$$R_{in} = \frac{R_F}{LG} \approx 0$$

$$R_{out} = \frac{1/g_{m4}}{LG} \approx 0$$

用于光通信的CMOS前置放大器



如果为全差分，
只需两级！

20 KΩ ... 500 Ω
of R_1 & R_f

Ref.: Phang, Johns, CAS-II July 1999

差分并联-并联反馈

$$A_R = R_F$$

$$LG = A_{V1}A_{V2}$$

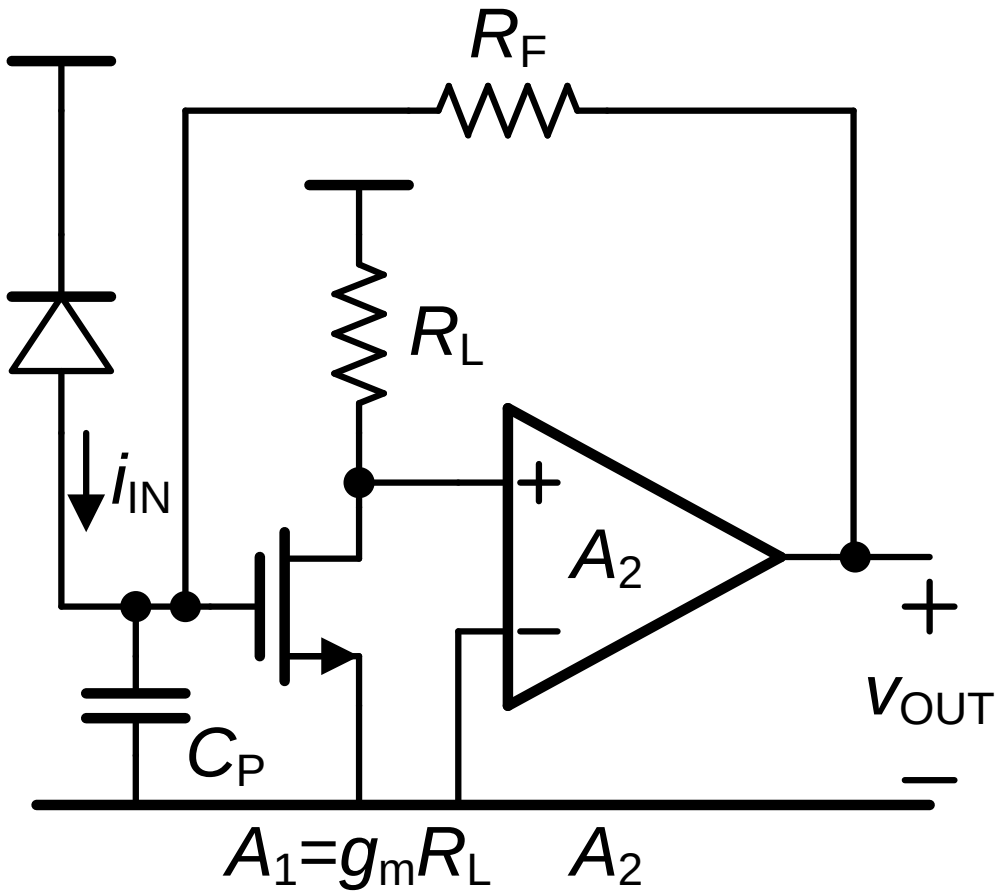
$$A_{V1} = g_{m1}r_{DS1}$$

$$A_{V2} = g_{m2}r_{DS2}$$

$$R_{in} = \frac{2R_F}{LG} \approx 0$$

$$R_{out} = \frac{2/g_{m3}}{LG} \approx 0$$

接电压放大器的电流检测器



$$R_{in} = \frac{v_{in}}{i_{in}} = \frac{R_F}{A_1 A_2}$$

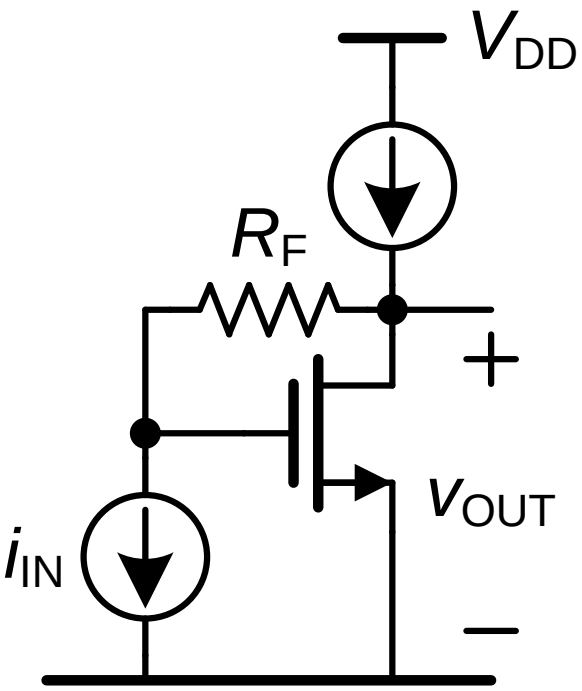
$$A_R = \frac{v_{out}}{i_{in}} = R_F$$

$$LG = A_1 A_2$$

$$f_{-3dB} = \frac{1}{2\pi R_{in} C_p}$$

Ref.: Cherry, Proc. IEE, Feb.63, 375-389

接并联-并联反馈的单管电路



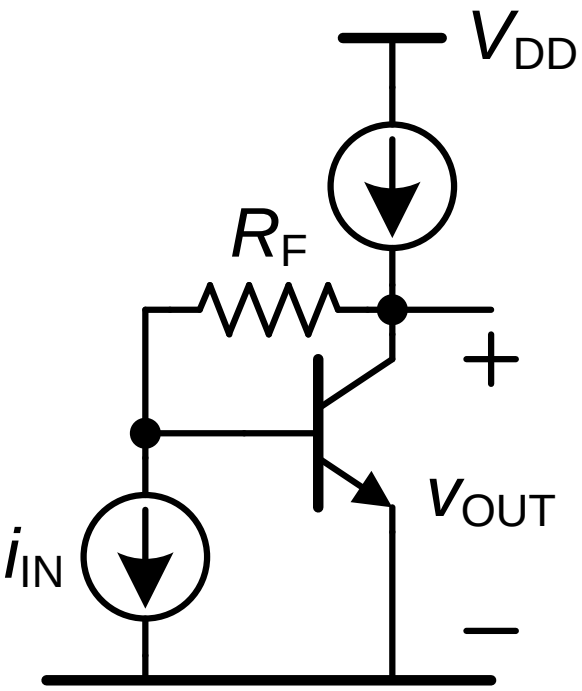
$$A_R = R_F(\text{if} \gg 1/g_m)$$

$$LG = g_m r_{DS}$$

$$R_{in} = \frac{R_F + r_{DS}}{LG} \approx 0\ ?$$

$$R_{out} = \frac{r_{DS}}{LG} \approx 0\ ?$$

接并联-并联反馈的单双极性晶体管



$$A_R = R_F(\text{if} \gg 1/g_m)$$

$$LG = \frac{g_m r_o r_\pi}{r_o + R_F + r_\pi}$$

$$R_{in} = \frac{(R_F + r_o)//r_\pi}{LG} \approx 0\ ?$$

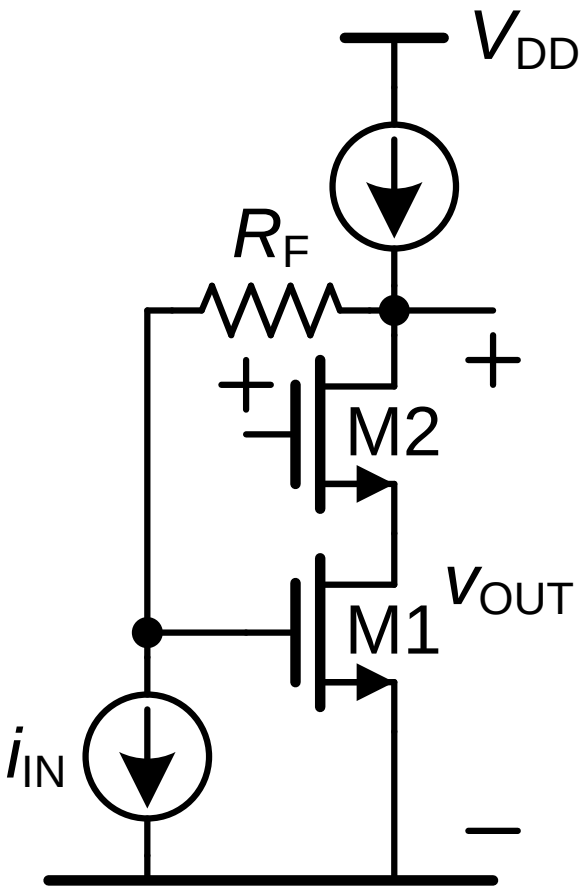
$$R_{out} = \frac{(R_F + r_\pi)//r_o}{LG} \approx 0\ ?$$

远非理想 !!

输出负载效应：$R_F+r_\pi \approx r_o$

降低了LG !!

共源共栅的并联-并联反馈



$$A_R = R_F$$

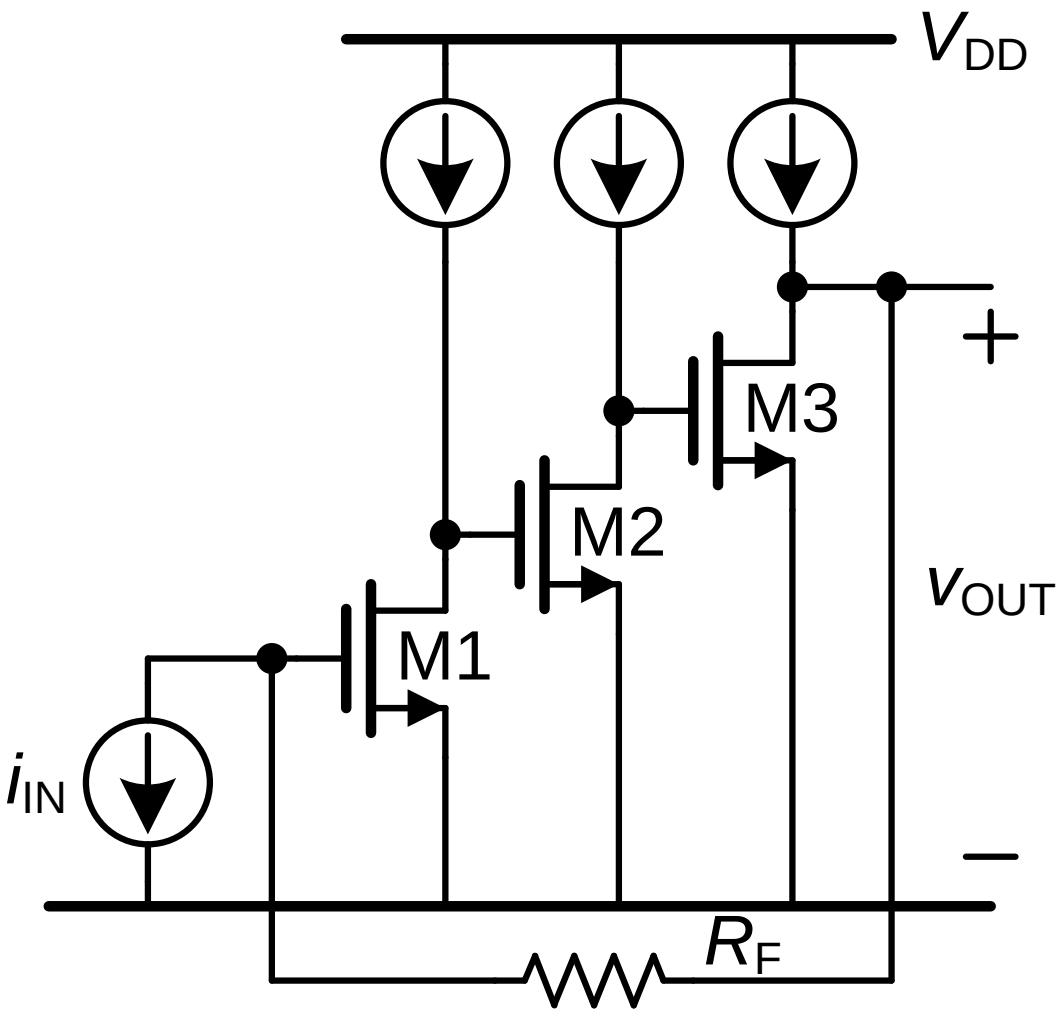
$$LG = g_{m1} r_{DS1} g_{m2} r_{DS2}$$

$$R_{in} = \frac{R_F + r_{out}}{LG} \approx \frac{1}{g_{m1}} \approx 0$$

$$r_{out} = r_{DS1} g_{m2} r_{DS2}$$

$$R_{out} = \frac{r_{out}}{LG} \approx \frac{1}{g_{m1}} \approx 0$$

MOS管并联–并联反馈



$$A_R = R_F$$

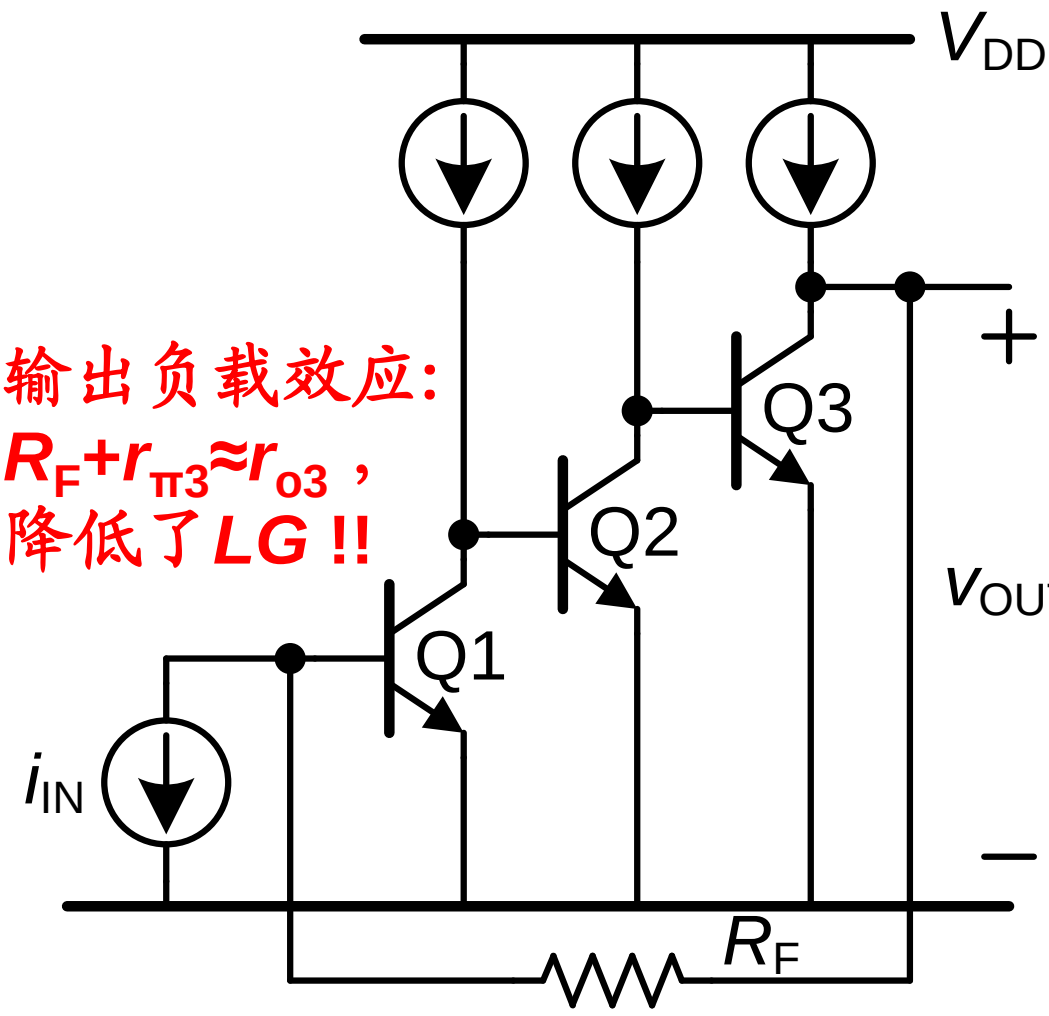
$$LG = A_{V1}A_{V2}A_{V3}$$

$$A_{Vi} = g_{mi}r_{DSi}$$

$$R_{in} = \frac{R_F + r_{DS3}}{LG} \approx 0$$

$$R_{out} = \frac{r_{DS3}}{LG} \approx 0$$

单双极性晶体管并联-并联反馈



输出负载效应：

$R_F+r_{\pi3}\approx r_{o3}$，降低了$LG$!!

$$A_R = R_F$$

$$LG = A_{V1}A_{V2}A_{V3}\frac{r_{\pi1}}{R_F + r_{\pi1}}$$

$$A_{V1} = g_{m1}(r_{o1}//r_{\pi2})$$

$$A_{V2} = g_{m2}(r_{o2}//r_{\pi3})$$

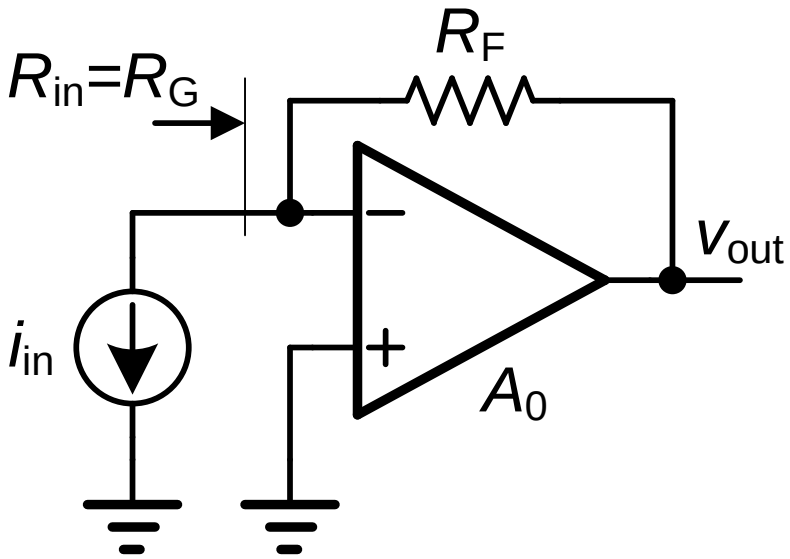
$$A_{V3} = g_{m3}R_{outOL}$$

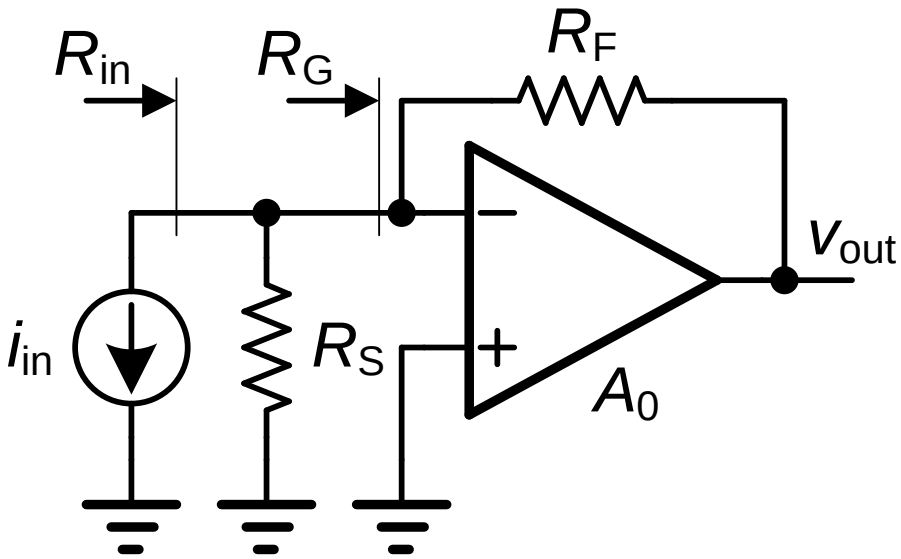
$$R_{outOL} = r_{o3}//(R_F + r_{\pi1})$$

$$R_{out} = \frac{R_{outOL}}{LG} \approx 0$$

$$R_{in} = \frac{(R_F + r_{o3})//r_{\pi1}}{LG} \approx 0$$

接非理想电流源的并联-并联反馈





$$A_R = R_F$$

$$LG = A_0$$

$$R_{in} = \frac{R_F}{A_0}$$

$$A_R = R_F$$

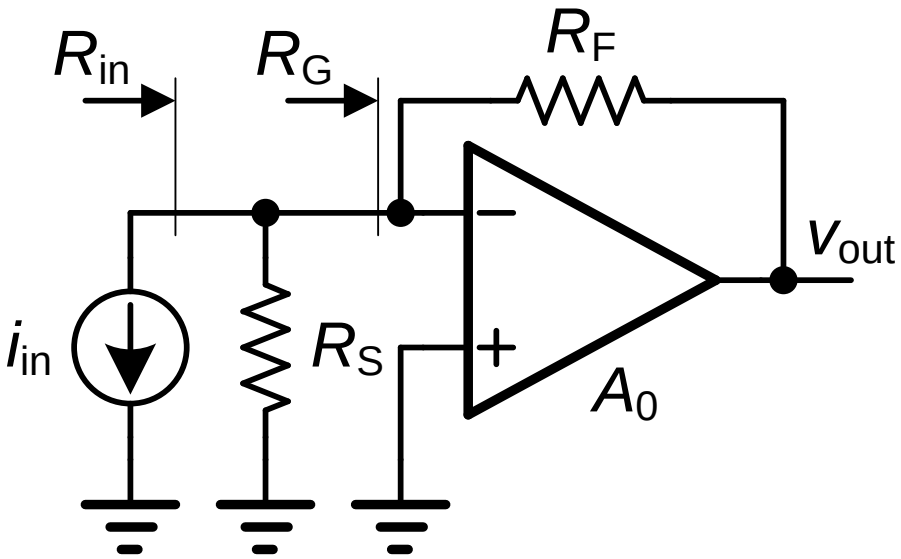
$$LG = A_0$$

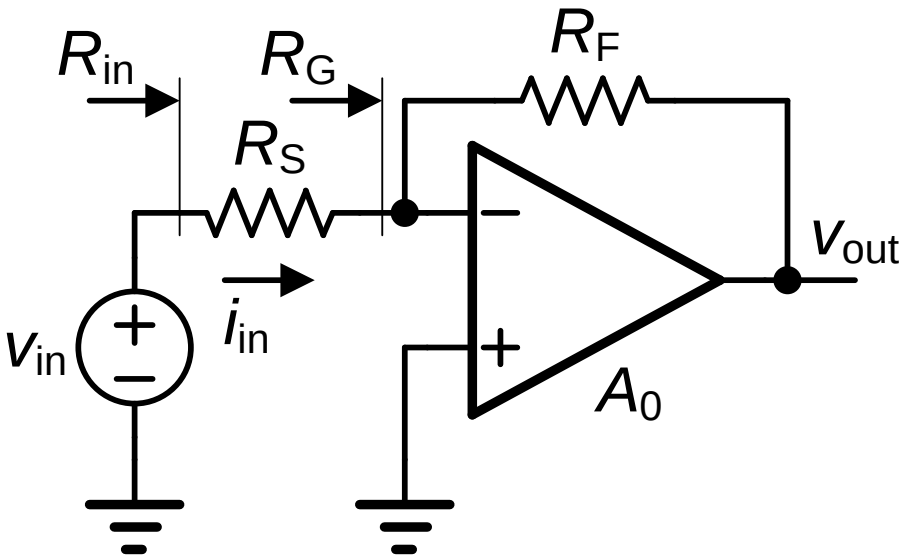
$$R_G = \frac{R_F}{A_0}$$

if $R_S > \dfrac{R_F}{A_0}$

$$R_{in} = R_G // R_S$$

接电压源的并联-并联反馈





$$A_R = R_F \quad \text{if } R_S > \frac{R_F}{A_0}$$

$$LG = A_0$$

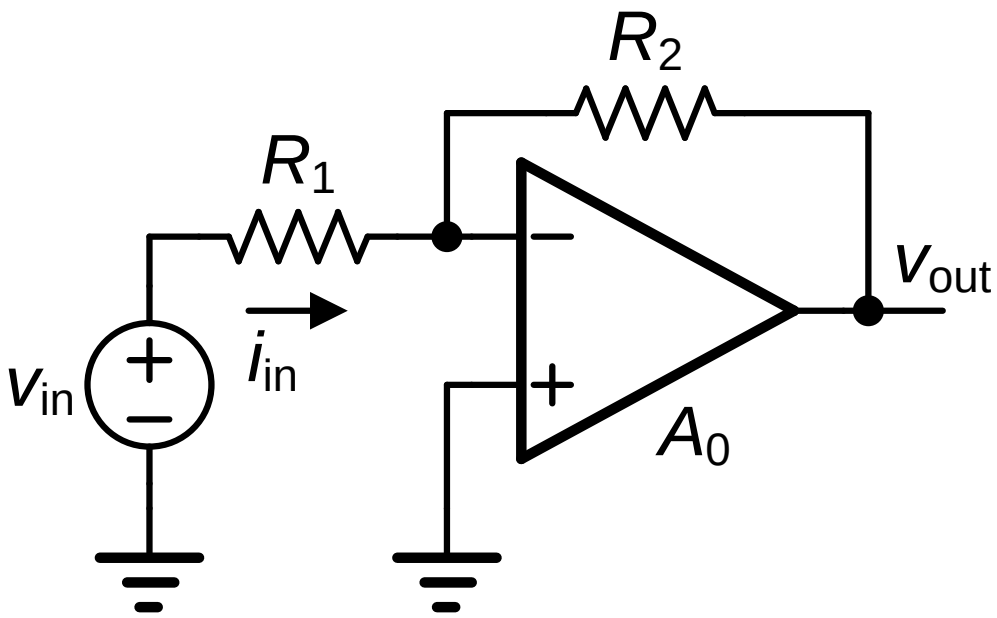
$$R_G = \frac{R_F}{A_0} \qquad R_{in} = R_G // R_S$$

$$A_R = R_F \quad \text{if } R_S > \frac{R_F}{A_0}$$

$$LG = A_0$$

$$R_G = \frac{R_F}{A_0} \qquad R_{in} = R_G + R_S$$

并联–并联反馈：增益和输出电阻



$$LG = A_0 \quad A_0 \approx 10^4 \ldots 10^6$$

$$A_R = R_2 \text{ if } R_1 > \frac{R_2}{A_0}$$

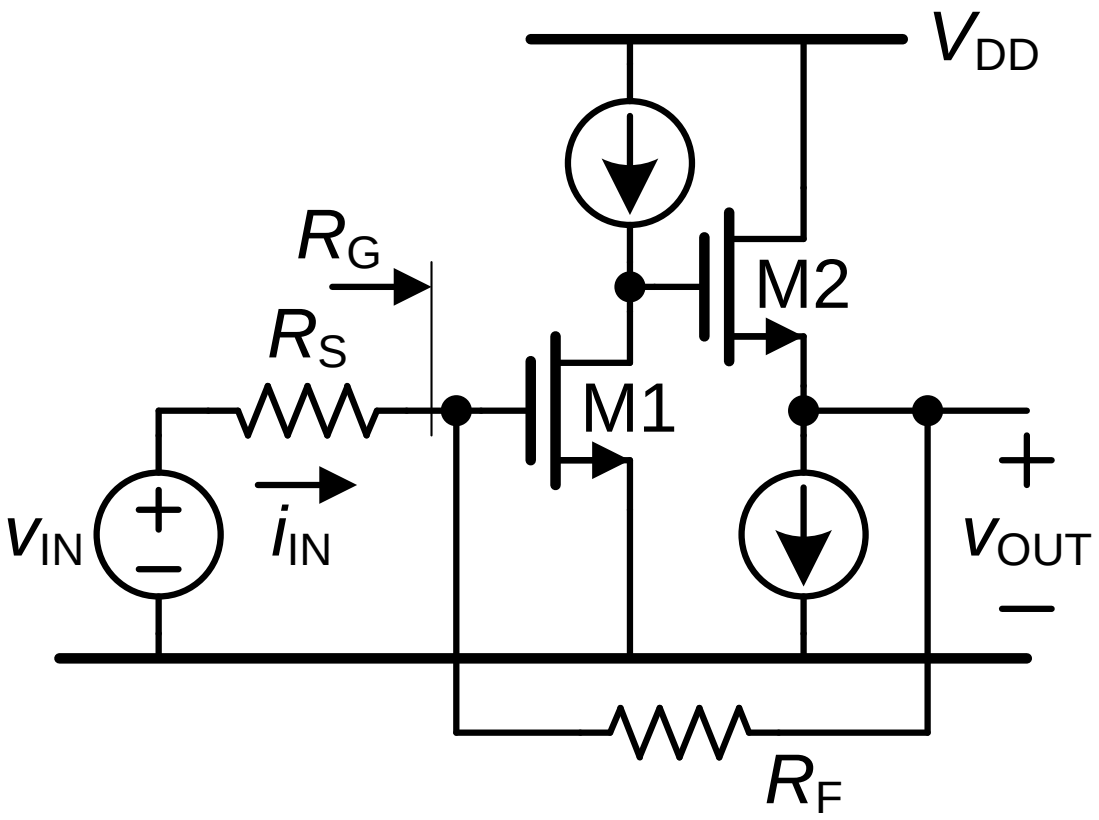
$$\frac{v_{out}}{v_{in}} = \frac{v_{out}}{i_{in}} \frac{i_{in}}{v_{in}}$$

$$A_V = -A_R \frac{1}{R_1}$$

$$= -\frac{R_2}{R_1}$$

$$R_{out} = \frac{R_{outOL}}{LG}$$

接电压源的并联-并联反馈



$$A_R = R_F$$

$$A_V = -\frac{R_F}{R_S}$$

$$LG = g_{m1} r_{DS1}$$

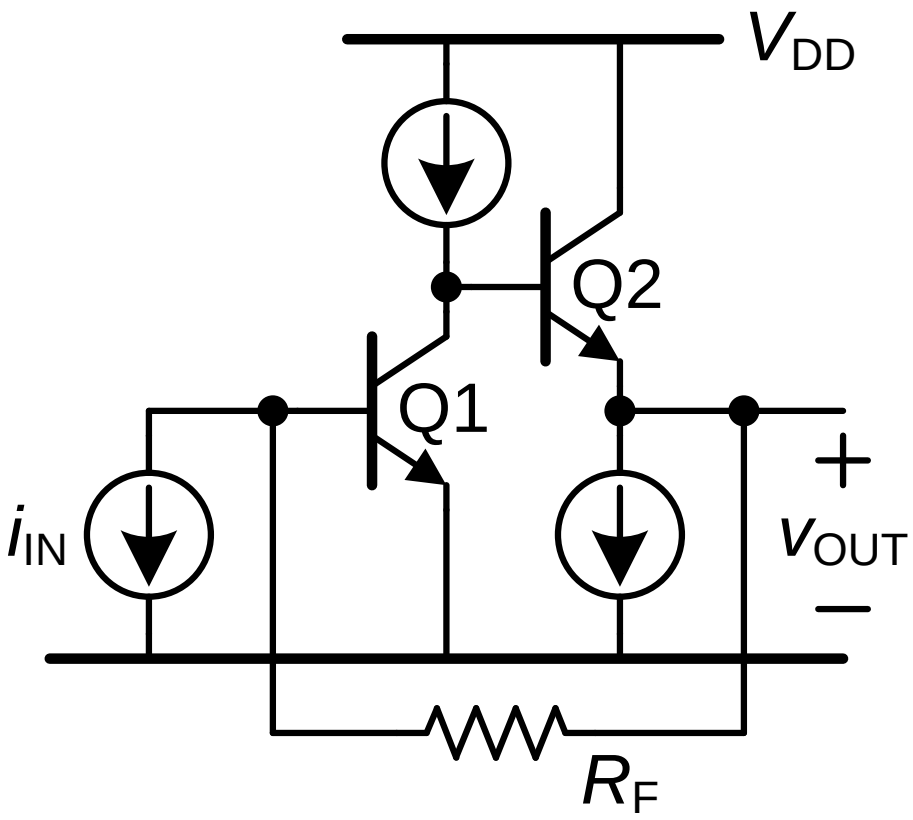
$$R_{in} = R_S + R_G$$

$$R_G = \frac{R_F}{LG} = \frac{R_F}{g_{m1} r_{DS1}} \approx 0$$

$$R_{out} = \frac{1/g_{m2}}{LG} \approx 0$$

if $R_S > \frac{R_F}{A_0}$

并联-并联反馈的输入负载效应



输入负载效应：$R_F \approx r_{\pi 1}$

$$A_R = R_F$$

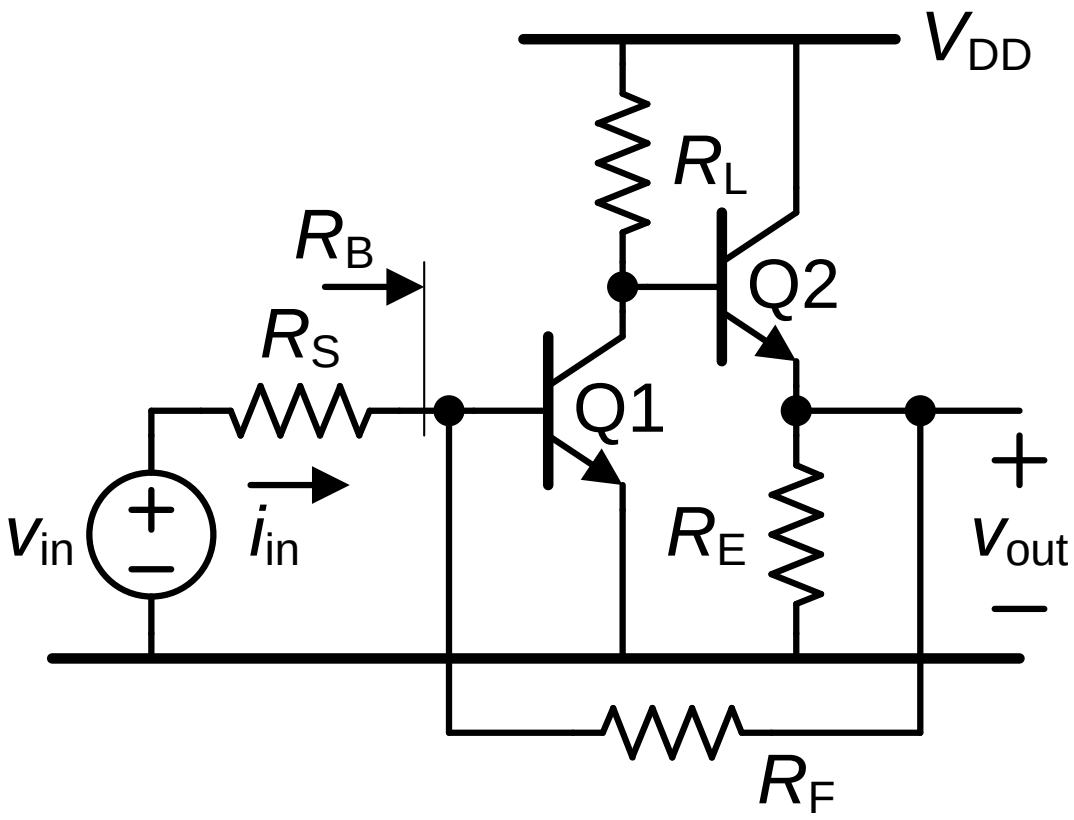
$$LG = g_{m1} r_{o1} \frac{r_{\pi 1}}{R_F + r_{\pi 1}}$$

$$R_{in} = \frac{R_F // r_{\pi 1}}{LG} = \frac{R_F}{g_{m1} r_{o1}} \approx 0$$

$$R_{out} = \frac{R_{outOL}}{LG} \approx 0$$

$$R_{outOL} = \frac{1}{g_{m2}} + \frac{r_{o1}}{\beta}$$

接电压源的并联-并联反馈



$$A_R = R_F$$

$$A_V = -\frac{R_F}{R_S}$$

$$LG = g_{m1}R_L\frac{r_{\pi 1}}{R_F + r_{\pi 1}}$$

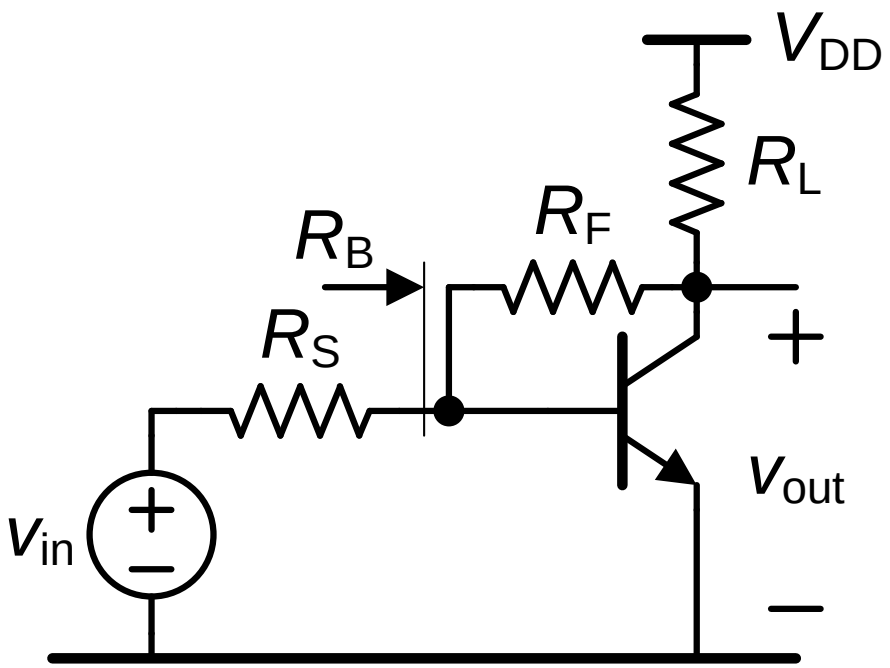
$$R_B = \frac{R_F // r_{\pi 1}}{LG} \approx 0$$

$$R_{in} = R_S + R_B$$

输入负载效应：$R_F \approx r_{\pi 1}$

$$R_{out} = \frac{R_{outOL}}{LG} \approx 0 \qquad R_{outOL} = \frac{1}{g_{m2}} + \frac{R_L}{\beta}$$

非理想单晶体管并联-并联反馈



$$A_R \approx R_F$$

$$A_V \approx -\frac{R_F}{R_S}$$

$$LG \approx g_{m1} r_{oLF}$$

$$R_{in} = R_S + R_B$$

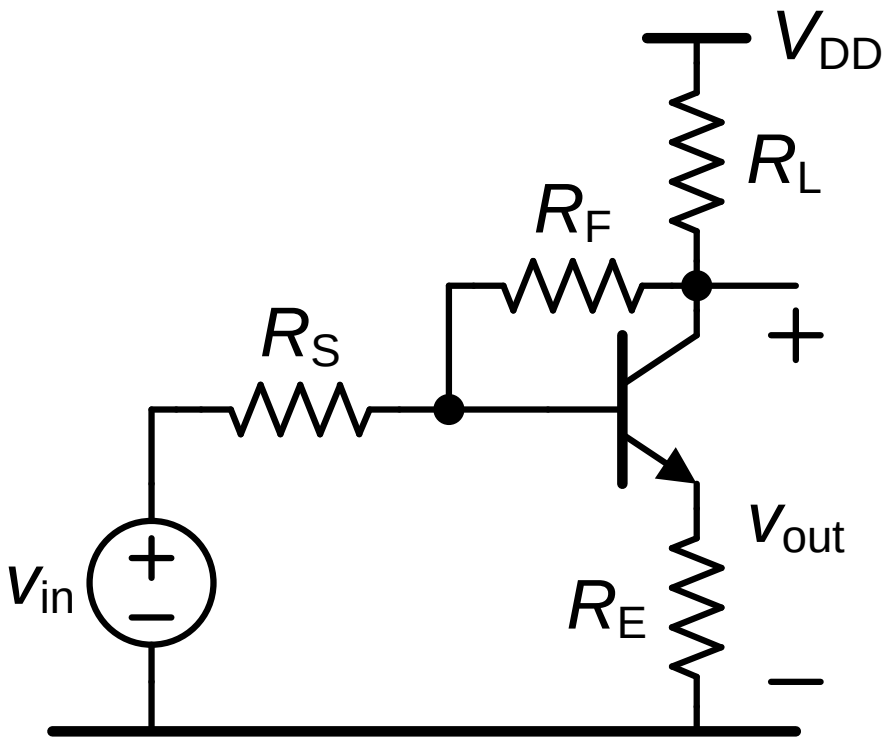
$$R_B \approx \frac{r_\pi // (R_F + r_{oL})}{LG} \approx 0$$

$$R_{out} \approx \frac{r_{oLF}}{LG} \approx 0 \ ??$$

输入负载效应：$R_F \approx r_{oL}$ $r_{oL} = r_o // R_L$ $r_{oLF} = r_o // R_L // R_F$

输出负载效应：$R_F \approx r_\pi$

非理想单晶体管反馈



$$A_R = R_F$$

$$A_V = -\frac{R_F}{R_S}$$

$$LG = ?$$

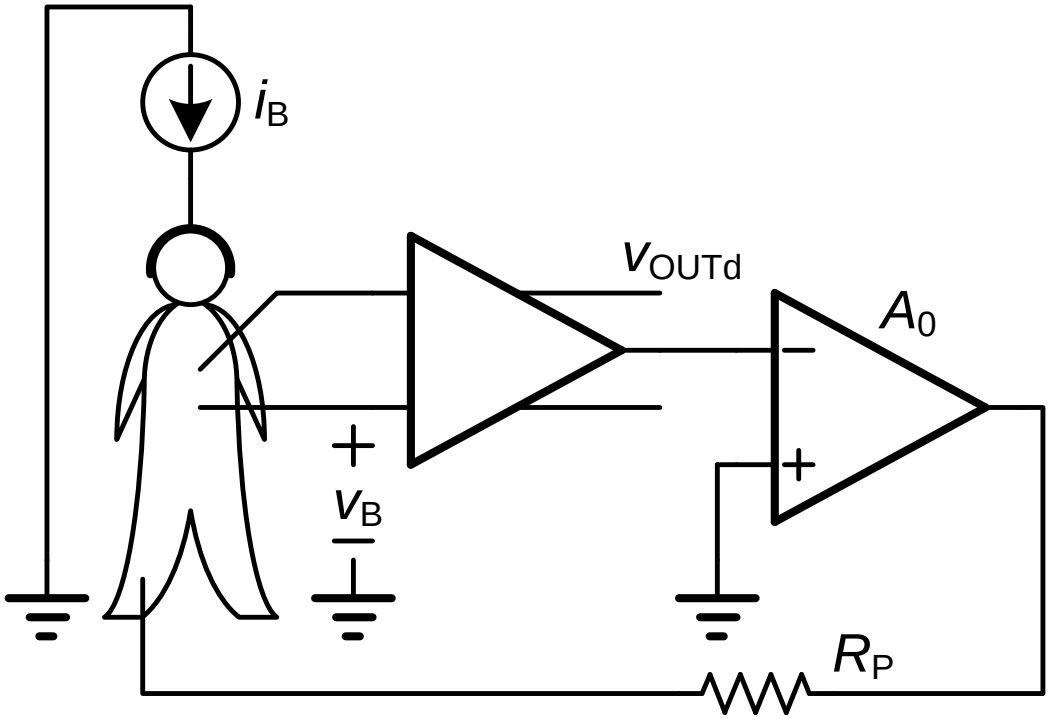
$$R_{in} = ?$$

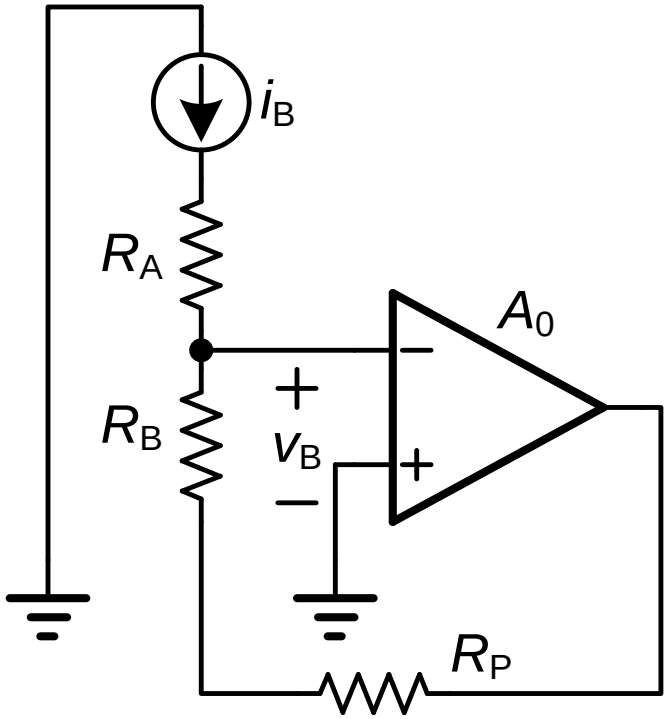
$$R_{out} = ?$$

输入负载效应：$R_F \approx r_{oL}$ $r_{oL} = r_o // R_L$

输出负载效应：$R_F \approx r_\pi$

ECG检测电路的并联–并联反馈



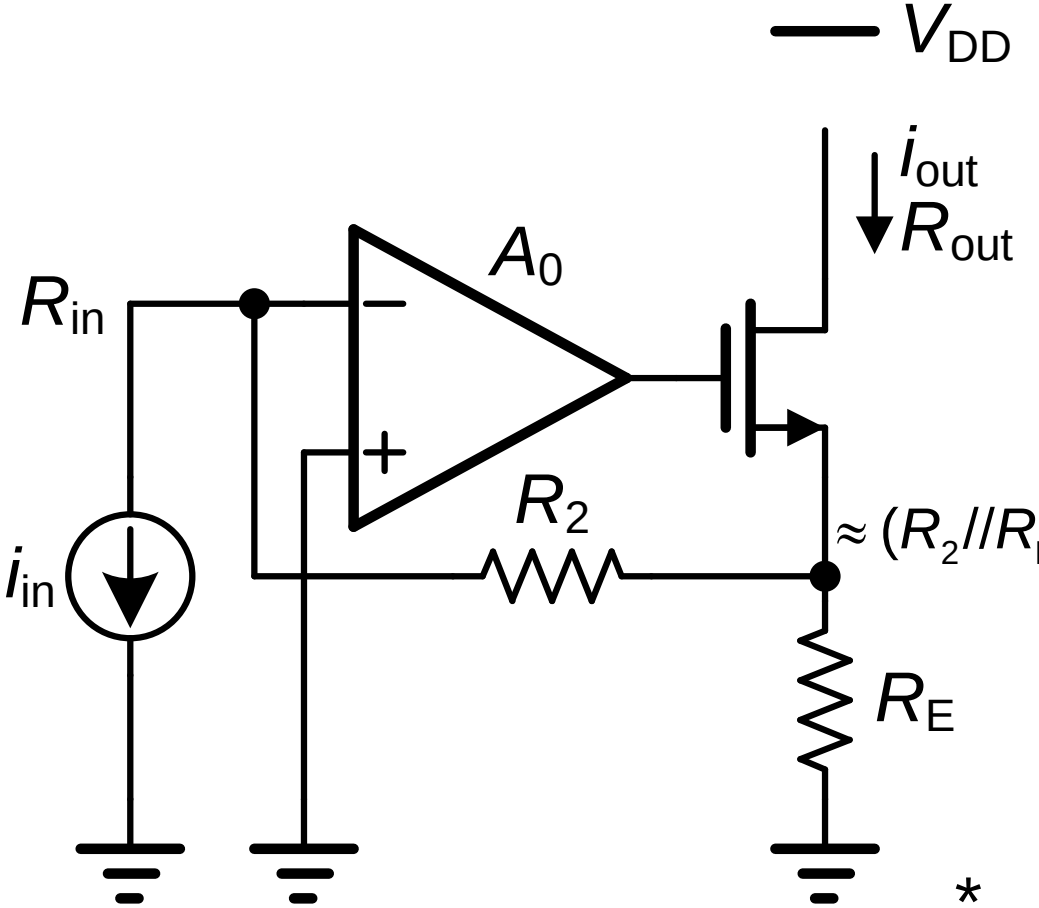


当220 V_{RMS}(50 Hz)经过150 pF的电容时 $i_B \approx 10\ \mu A_{RMS}$

$$\frac{v_B}{i_B} = \frac{R_P + R_B}{A_0 + 1}$$

目录

并联–串联反馈：增益、R_{in}和R_{out}



$$LG = A_0$$

$$A_I = 1 + \frac{R_2}{R_E}$$

$$R_{in} = \frac{R_2^*}{LG}$$

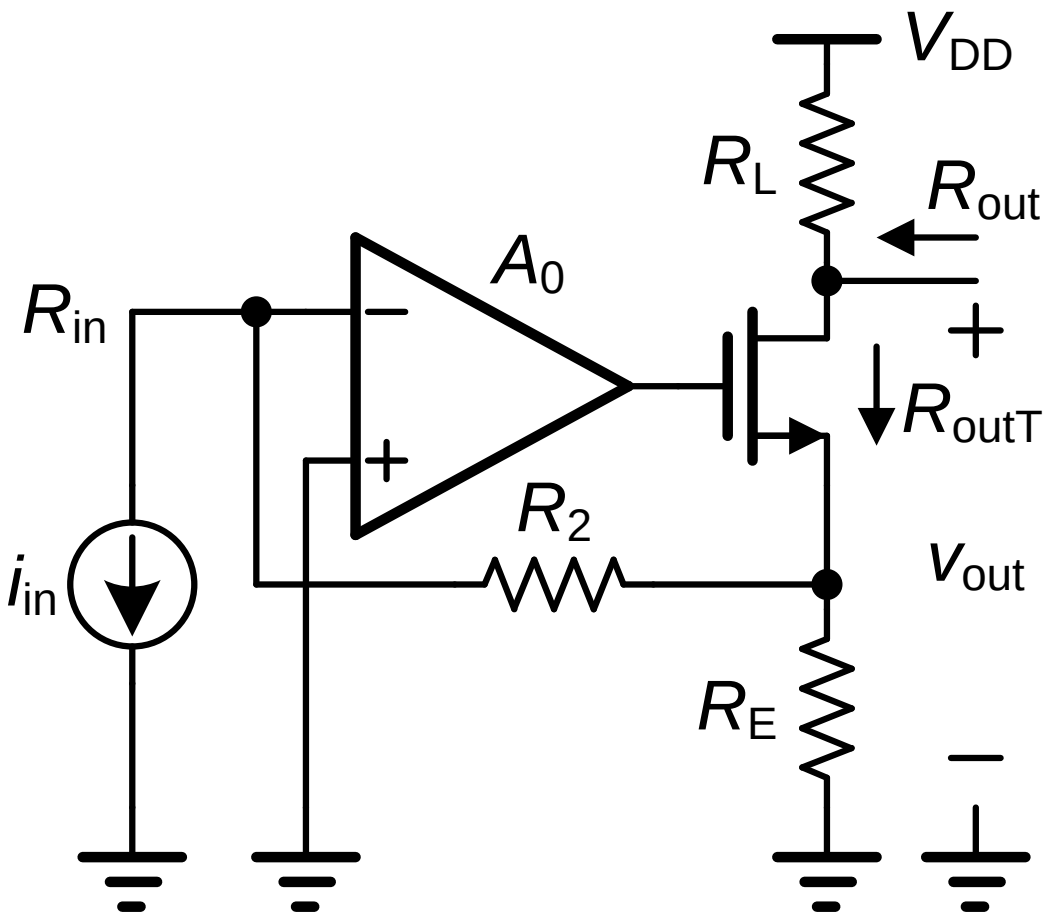
$$R_{outOL} = r_{DS}(1 + g_m R_E)$$

$$R_{out} = R_{outOL} LG \approx \infty$$

$$R_2^* = R_2 + R_E/(1 + g_m R_E) \approx R_2$$

$$R_E > 1/g_m \quad R_2 > 1/g_m$$

接负载R_L的并联-串联反馈



$$LG = A_0$$

$$A_I = 1 + \frac{R_2}{R_E}$$

$$A_R = A_I R_L$$

$$R_{in} = \frac{R_2^*}{LG} \approx 0$$

$$R_{out} = R_{outT} // R_L \approx R_L$$

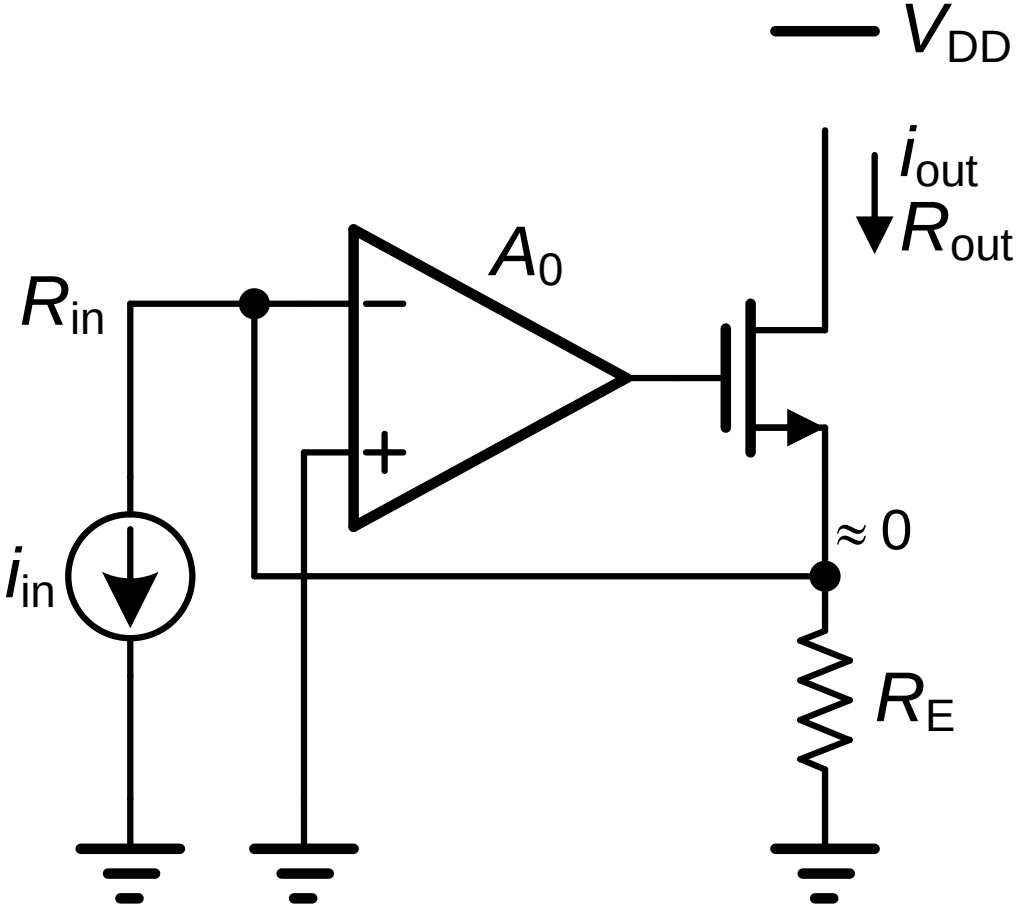
$$R_{outT} = R_{outTOL} LG \approx \infty$$

$$R_{outTOL} = r_{DS}(1 + g_m R_E)$$

$$R_E > 1/g_m \quad R_2 > 1/g_m$$

$$R_2^* = R_2 + R_E/(1 + g_m R_E) \approx R_2$$

理想电流缓冲器



$$A_I = 1$$

$$LG = A_0$$

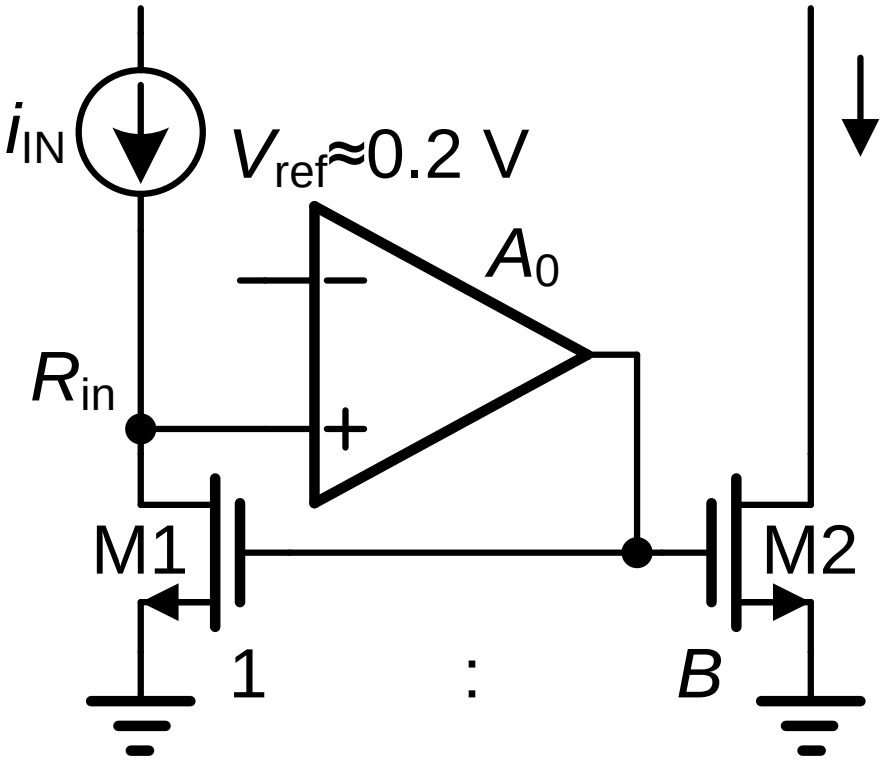
$$R_{in} = \frac{1/g_m}{LG} \approx 0$$

$$R_{outOL} = r_{DS}(1 + g_m R_E)$$

$$R_{out} = R_{outOL} LG \approx \infty$$

$$R_E > 1/g_m$$

理想电流镜



$$A_I = B$$

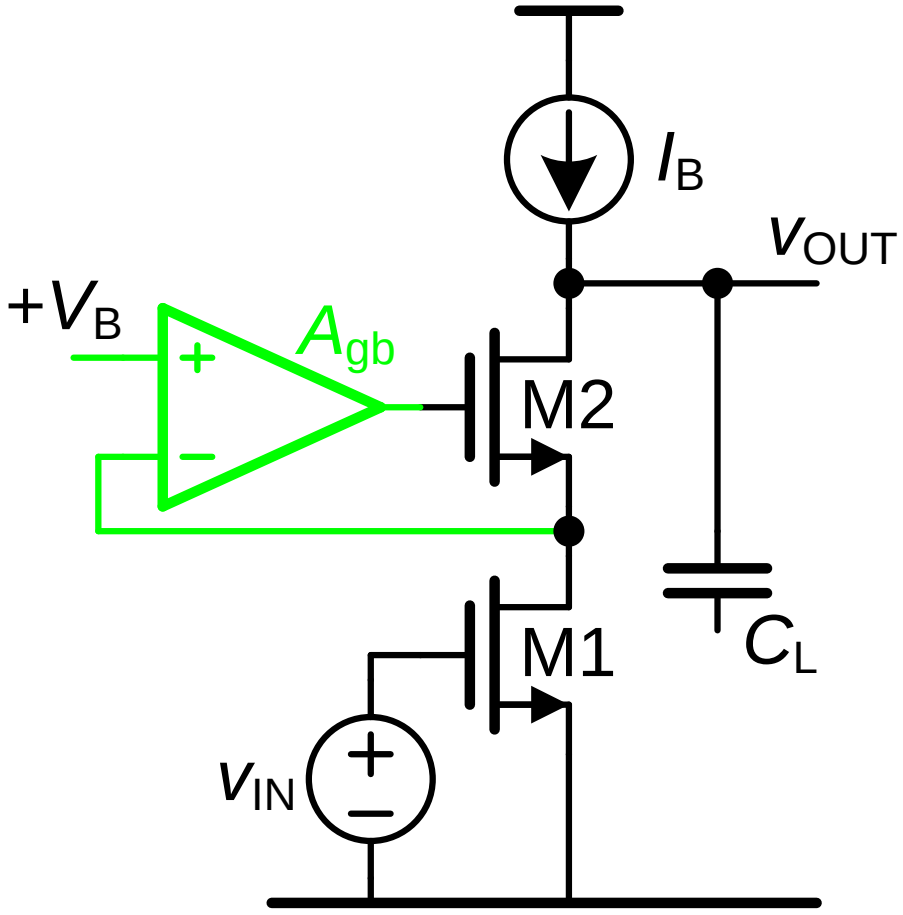
$$LG = g_{m1} r_{DS1} A_0$$

$$R_{in} = \frac{R_{inOL}}{LG} = \frac{1}{g_{m1} A_0} \approx 0$$

$$R_{inOL} = r_{DS1}$$

$$R_{out} = r_{DS2}$$

增益抬升



$$LG = A_{gb}$$

$$R_{E2} = \frac{1/g_{m2}}{LG} \approx 0$$

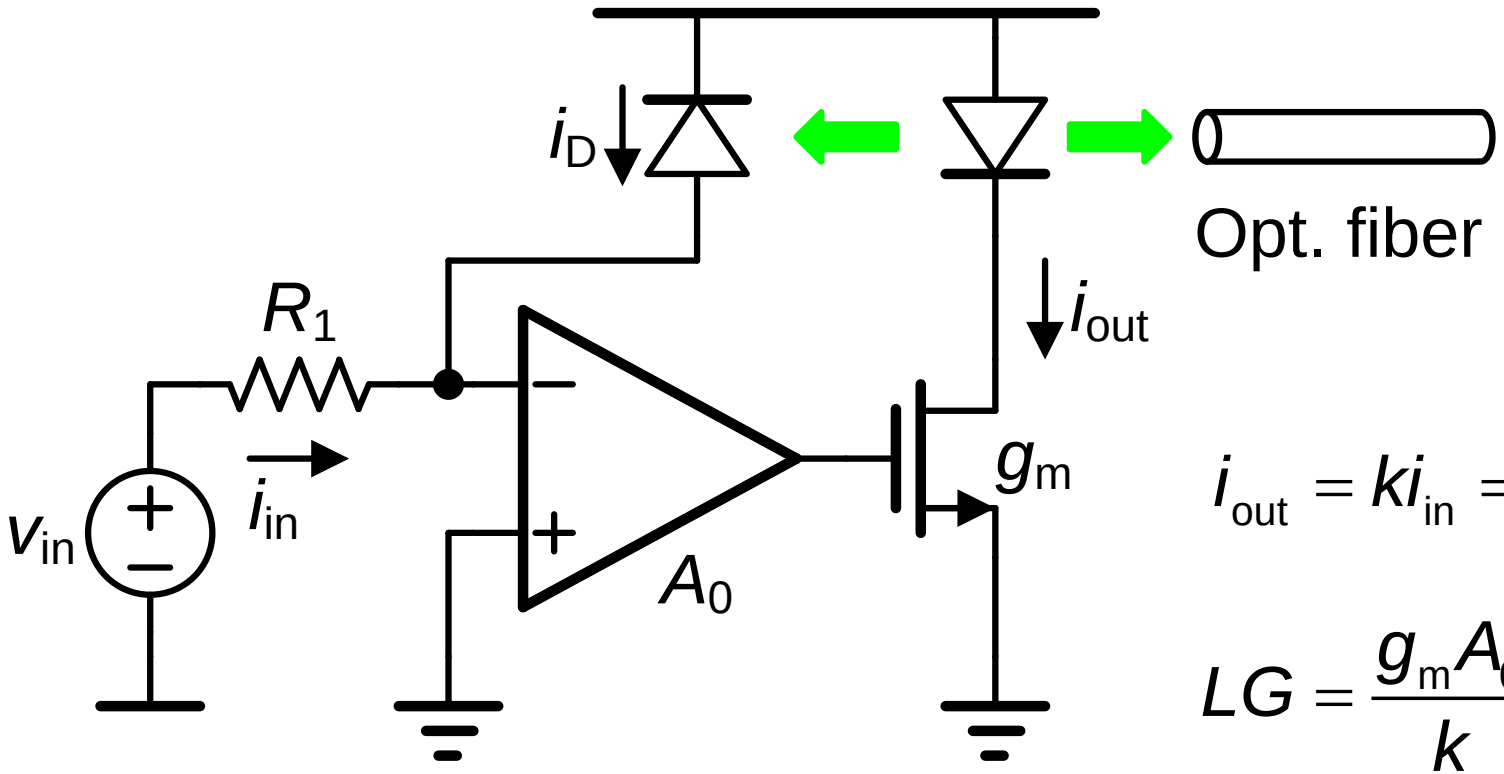
$$R_{outOL} = r_{DS2}(1 + g_{m2}r_{DS1})$$

$$R_{out} = R_{outOL}LG \approx \infty$$

$$A_V = A_{gb}(g_m r_{DS})_1(g_m r_{DS})_2$$

Ref.: Hosticka, JSSC Dec.79, pp. 1111-1114; Sackinger, JSSC Febr.90, pp. 289-298; Bult JSSC Dec.90, pp. 1379-1384

线性发光二极管驱动器



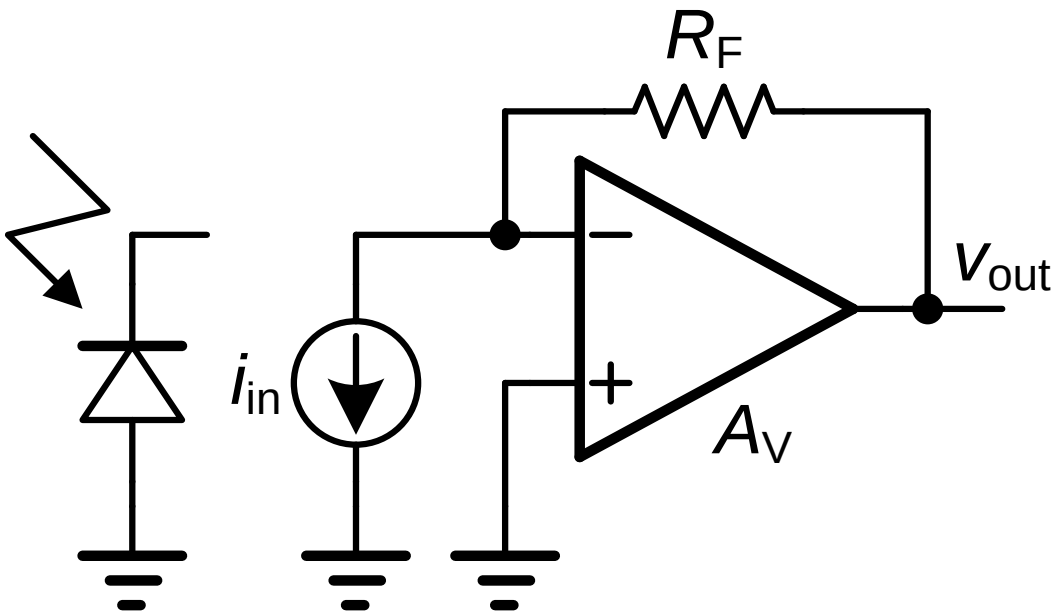
$$i_{out} = ki_{in} = k\frac{v_{in}}{R_1}$$

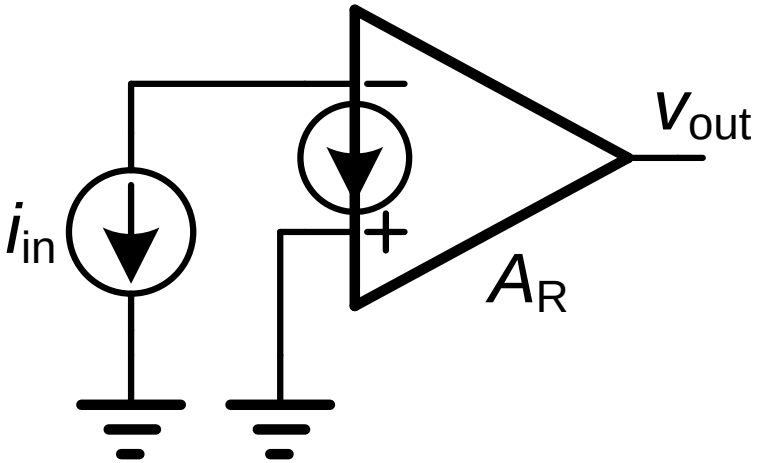
$$LG = \frac{g_m A_0}{k}$$

$$i_D = \frac{i_{out}}{k}$$

目录

光接收器：电流或电压放大器

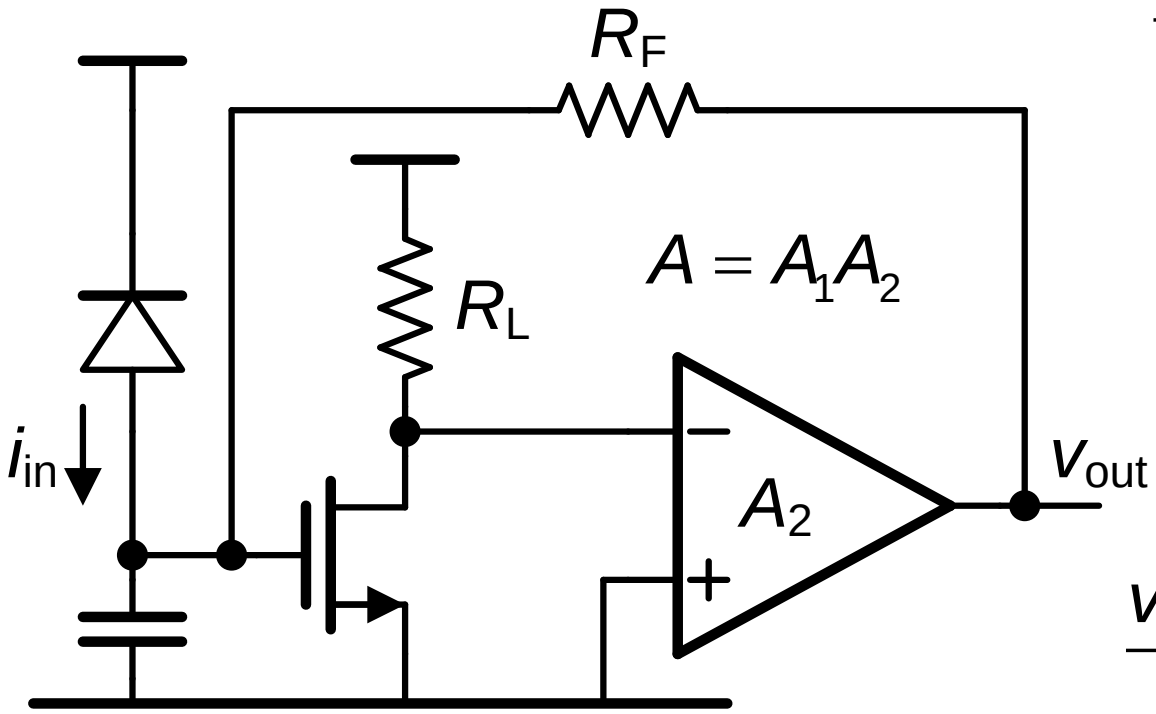




$$v_{out} = R_F i_{in}$$

$$v_{out} = A_R i_{in}$$

接电压放大器的电流检测器 1



$$\frac{v_{in}}{i_{in}} = \frac{1}{sC_p} // \frac{R_F}{A_1A_2}$$

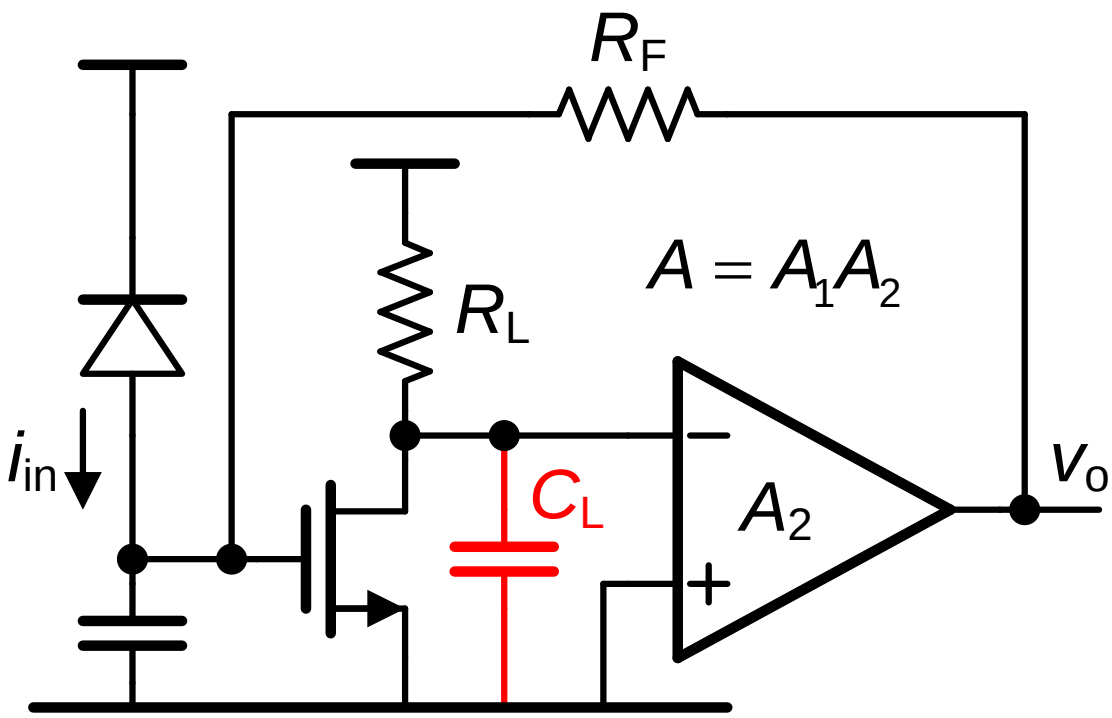
$$= \frac{R_F}{A_1A_2} \frac{1}{1 + R_F \frac{C_p}{A_1A_2} s}$$

$$\frac{v_{out}}{i_{in}} = R_F \frac{1}{1 + R_F \frac{C_p}{A_1A_2} s}$$

噪声匹配: $C_D = C_{GS}$

$$A_R BW(\text{THz}\Omega) = \frac{A_1A_2}{2\pi C_p}$$

接电压放大器的电流检测器 2



$$\frac{v_{in}}{i_{in}} = \frac{R_F}{A_1A_2}\frac{1+R_LC_Ls}{1+as+bs^2}$$

$$a = \frac{R_FC_p}{A_1A_2}$$

$$b = \frac{R_FC_pR_LC_L}{A_1A_2}$$

$$\frac{v_{out}}{i_{in}} = R_F\frac{1}{1+as+bs^2}$$

$$C_p = C_D + C_{GS} \quad A_1 = g_mC_L$$

如果 $R_L < \sqrt{\frac{R_F}{4g_mA_2}\frac{C_p}{C_L}}$，则没有峰值

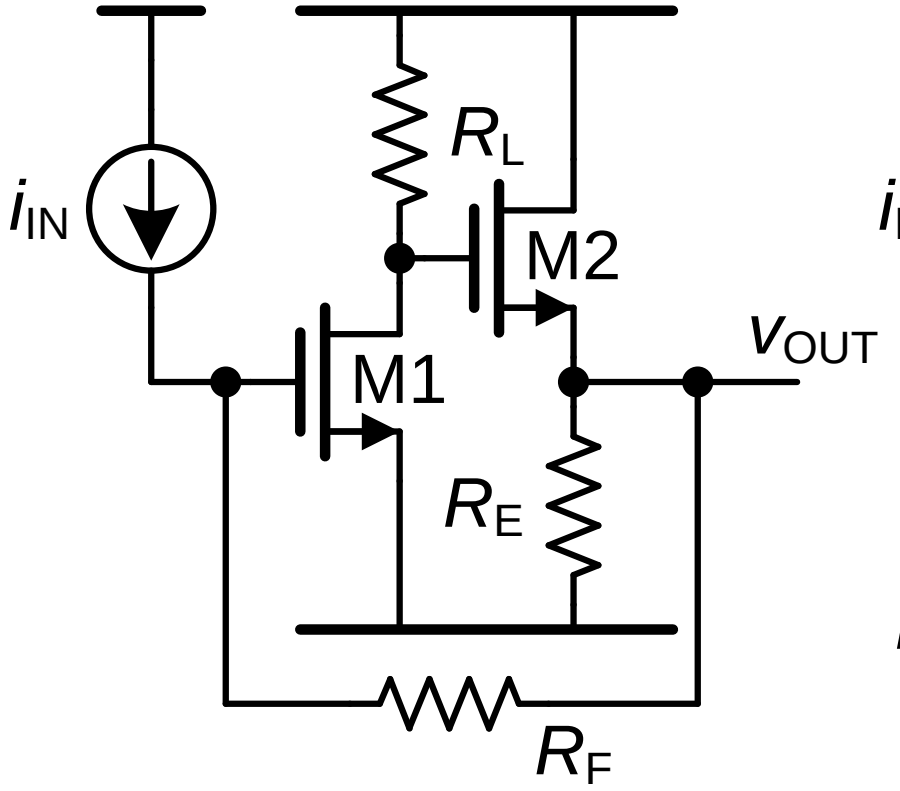
接电压放大器的电流检测器 3

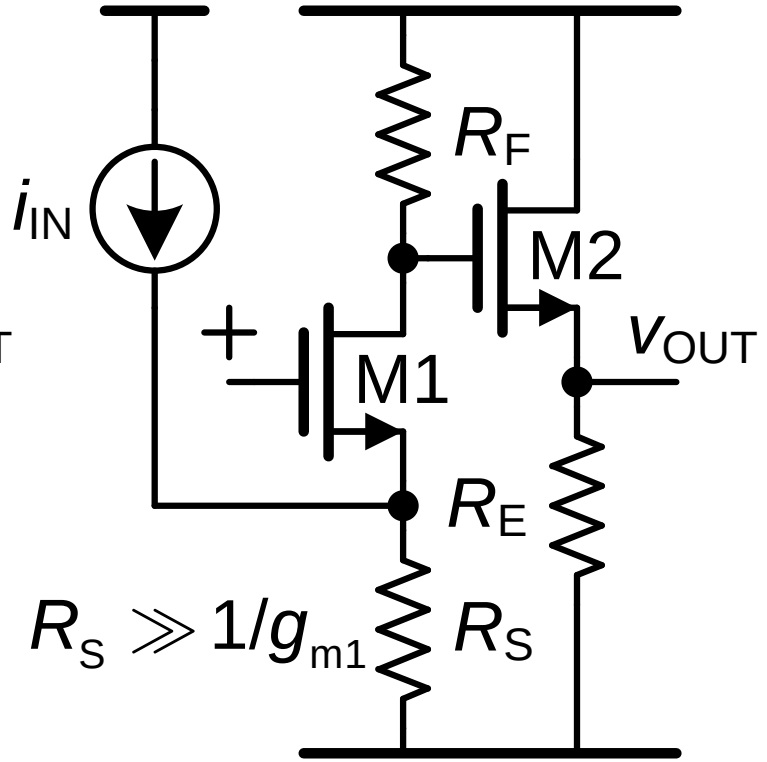
$$\frac{v_{in}}{i_{in}} = \frac{R_F}{\boxed{\frac{A_1}{1+R_L C_L s}} A_2} \frac{1}{1+R_F \frac{C_p}{\boxed{\frac{A_1}{1+R_L C_L s}} A_2} s}$$

$$= \frac{R_F}{A_1 A_2} \frac{1+R_L C_L s}{1+\frac{R_F C_p}{A_1 A_2} s + \frac{R_F C_p R_L C_L}{A_1 A_2} s^2}$$

$$\left(\frac{R_F C_p}{A_1 A_2}\right)^2 - 4\frac{R_F C_p R_L C_L}{A_1 A_2} > 0 \overset{A_1 = g_m R_L}{\Rightarrow} R_L < \sqrt{\frac{R_F}{4 g_m A_2} \frac{C_p}{C_L}}$$

电压/电流放大器的带宽：BW

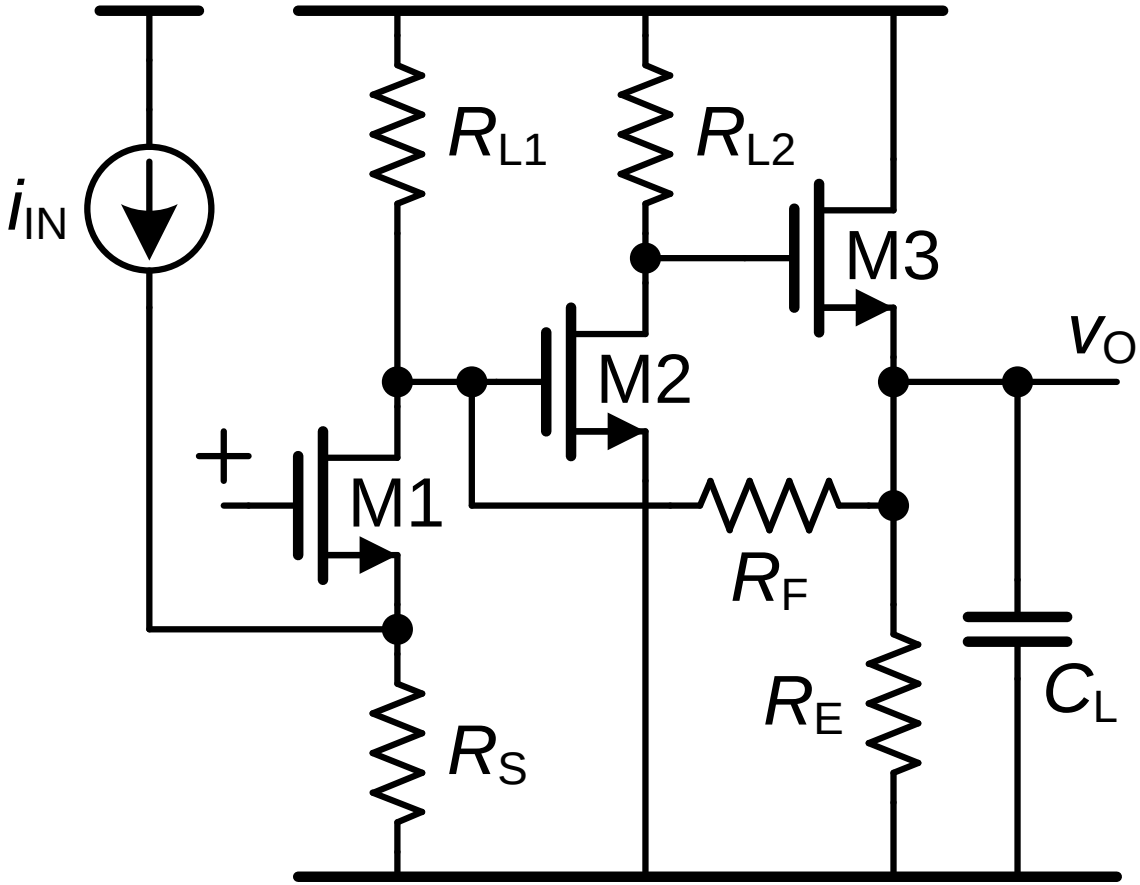




$$BW = \frac{A_{V1}}{2\pi R_F (C_{GS1} + C_D + A_{V1} C_{GD1})}$$

$$BW = \frac{1}{2\pi R_F (C_{DG2} + C_{DB1})}$$

接共源共栅输入的电流检测器



$$BW = \frac{1}{2\pi(\frac{R_F}{A_{V2}} // R_{L1})C_T}$$

$$C_T = C_{GS2} + A_{V2}C_{GD2}$$

$$A_{V2} = g_{m2}R_{L2}$$

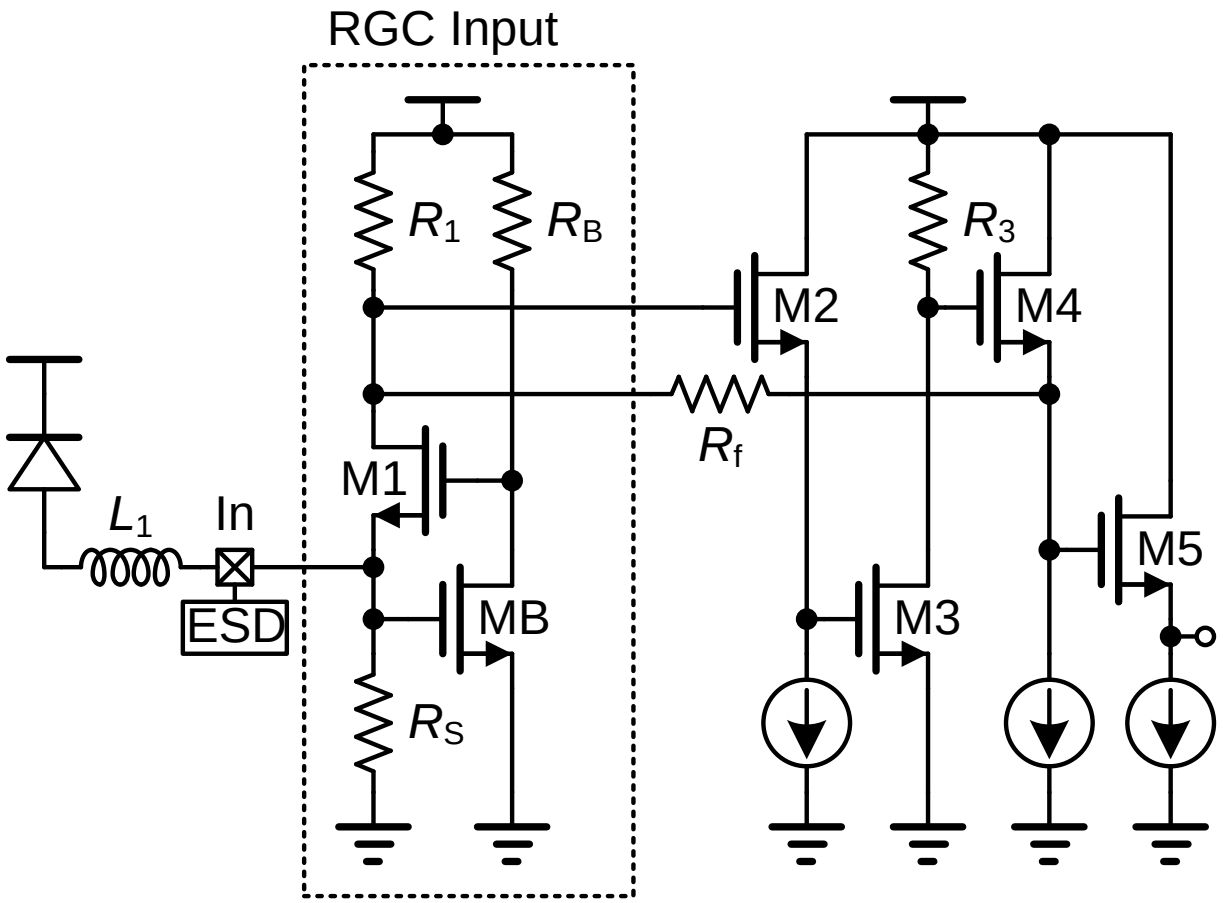
$$v_{out} = R_F i_{in}$$

$$R_{out} = \frac{1/g_{m3}}{A_{V2}}$$

$$R_S \gg 1/g_{m1}$$

Z_{in}与f无关！

Ref.: Vanisri, etal, JSSC June 95, pp. 677-685



5 V 17 mA

$C_D = 0.5$ pF

$R_F = 800\ \Omega$

$BW = 1$ GHz

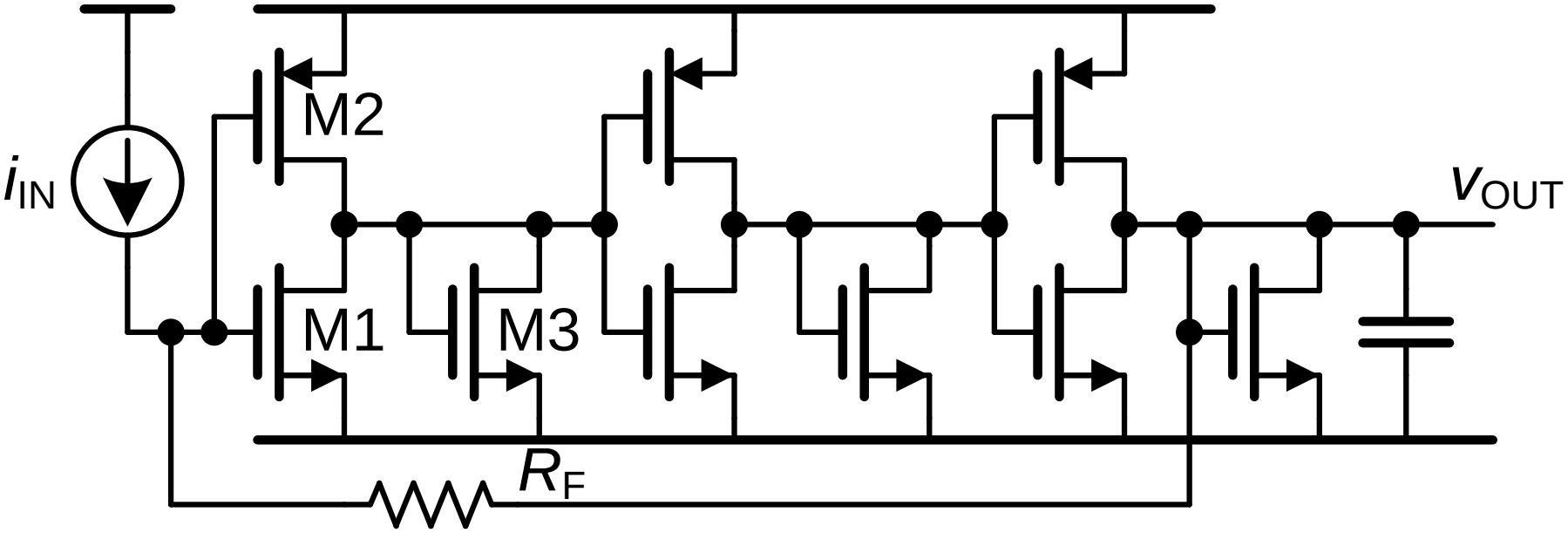
$g_{mB} = 3g_{m1}$

BW与C_D无关！

电流噪声：R_S和$R_F//R_1$

Ref.: Vanisri, etal, JSSC June 95, pp. 677-685

CMOS光敏二极管放大器

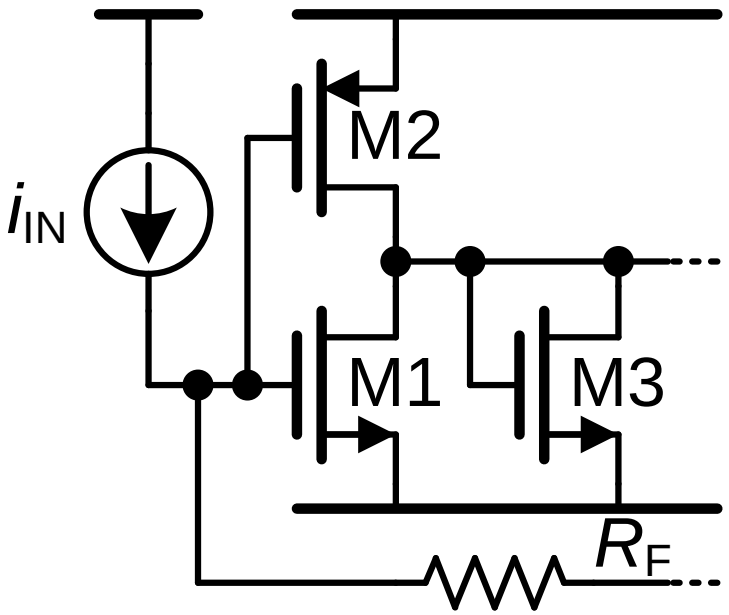


$150\ \mathrm{K\Omega} \times 120\ \mathrm{MHz} = 18\ \mathrm{THz\Omega}$ $0.5\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$

450 MHz per cell

Ref.: Ingels, JSSC Dec 1994, 1552-1559

CMOS宽带放大器核心单元



M1和M3：有相同的V_{GS}和V_{DS}

$$K_n' \approx 2K_p'$$

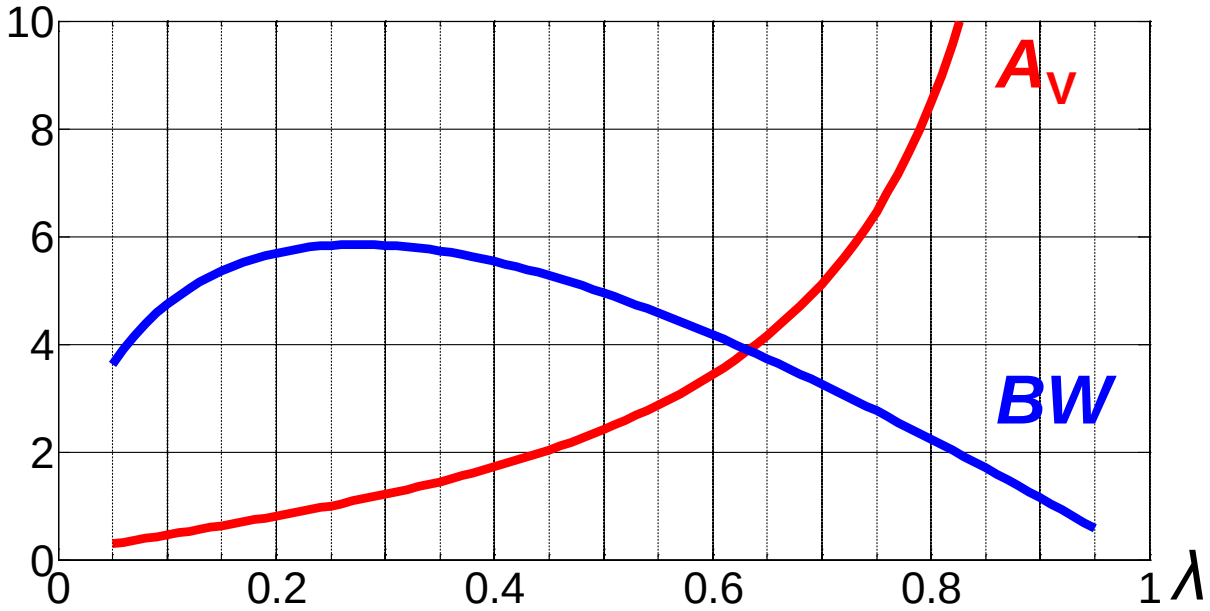
所有L均为L_{min}

$$A_V = \frac{g_{m1} + g_{m2}}{g_{m3}}$$

$$g_m = 2\sqrt{K_n' I_{DS} W/L}$$

$$I_{DS1} = \lambda I_{DS2} \quad I_{DS3} = (1-\lambda) I_{DS2} \qquad V_{GS1} = V_{GS3} : W_3 = W_1 \frac{1-\lambda}{\lambda}$$

CMOS宽带放大器: 增益和带宽



$$\frac{\lambda}{1-\lambda}\left(1+\sqrt{\frac{W_2}{2\lambda W_1}}\right)$$

$$BW = \frac{g_{m3}}{2\pi C_n}$$

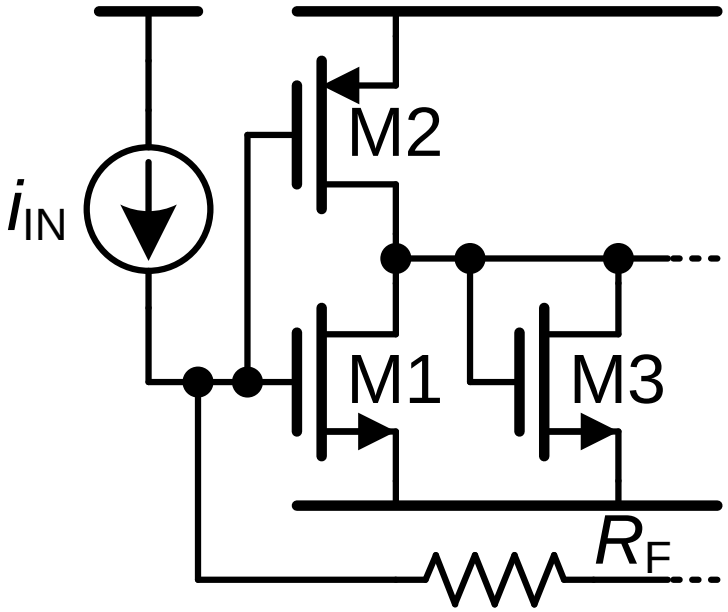
$$\sim \frac{(1-\lambda)\sqrt{\lambda W_1}}{W_1(2-\lambda)+\lambda W_2}$$

$W_1 = 2 \quad W_2 = 4$

$C_n = C_{DB1} + C_{GS3} + C_{DB3} + C_{DB2}$

$C_{DB} \approx C_{GS} \approx kW \quad k \approx 2$ fF/μm

集成电阻



R_F? 多晶硅电阻：大尺寸：长L

分布电容:

在100 MHz处45˚相移

$$f_{-3dB} = \frac{1}{2\pi} \frac{2.43}{R_S C_0 L^2}$$

$$R_S = \text{sheet res.}(\Omega/\square)$$

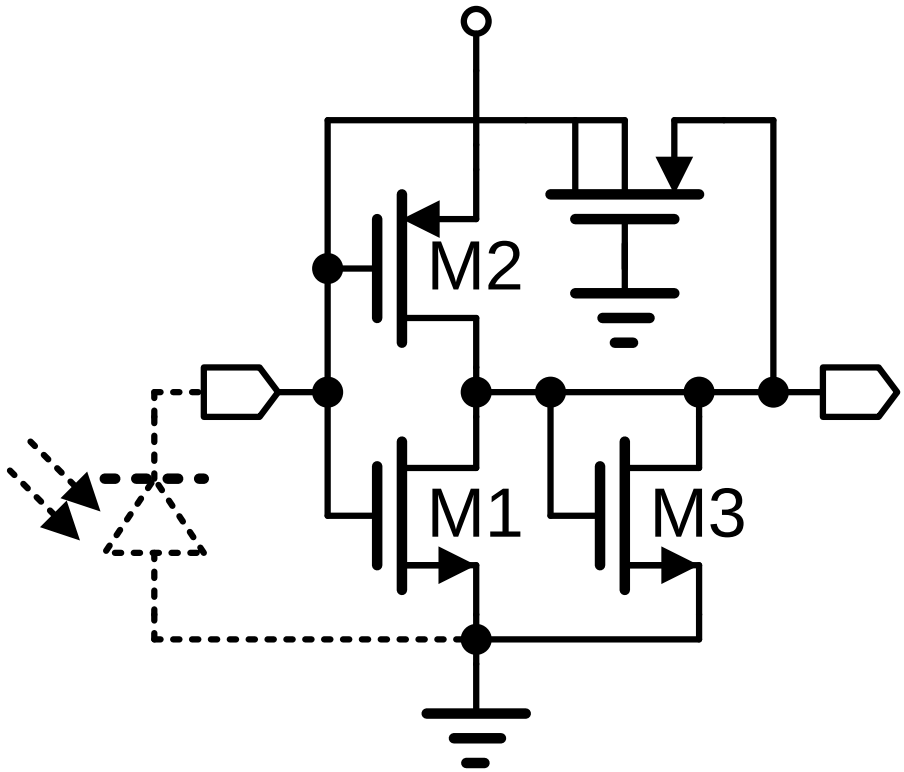
$$C_0 = \text{unit cap.}(\text{F/cm}^2)$$

MOST : W = 1.3 μm & L = 1 μm

允许动态压缩

Ref.: Glaser; IC Engineering Add.Wesley, p.132

1 Gb/s 1 KΩ 跨导级



C_d = 0.8 pF ≈ C_{GS}

容性噪声匹配！

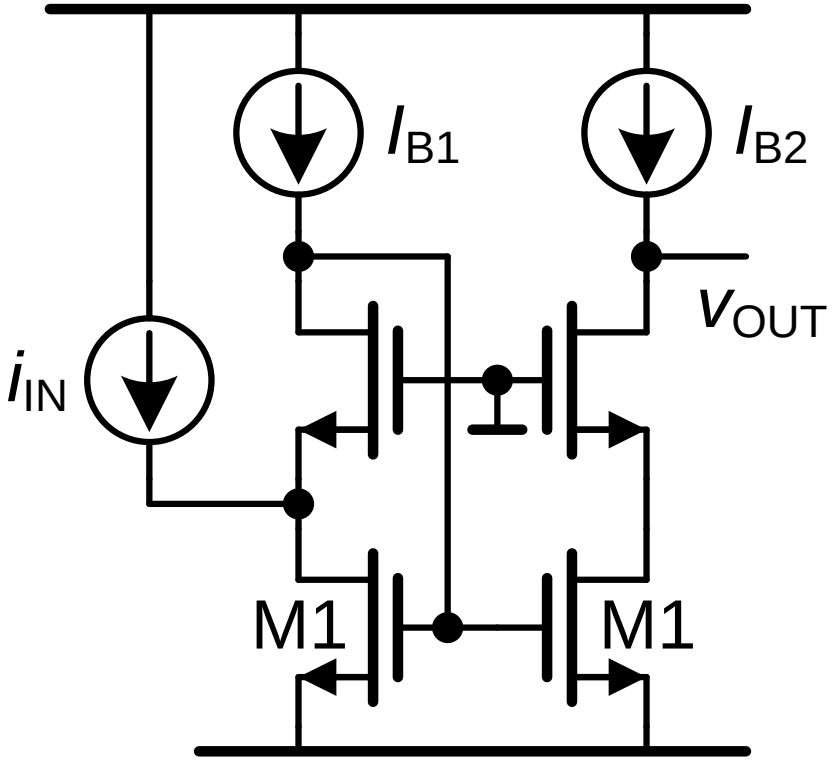
BW = 500 MHz

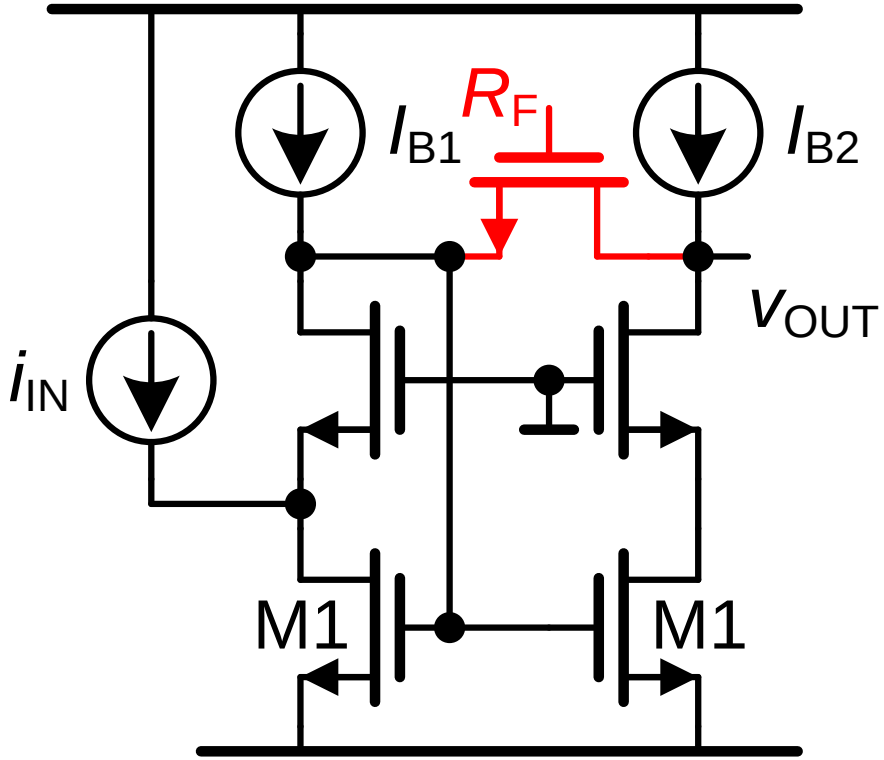
5 mA (5V)

0.7 μm CMOS

Ref.: Ingels, JSSC July 1999, 971-977

低电压跨阻放大器

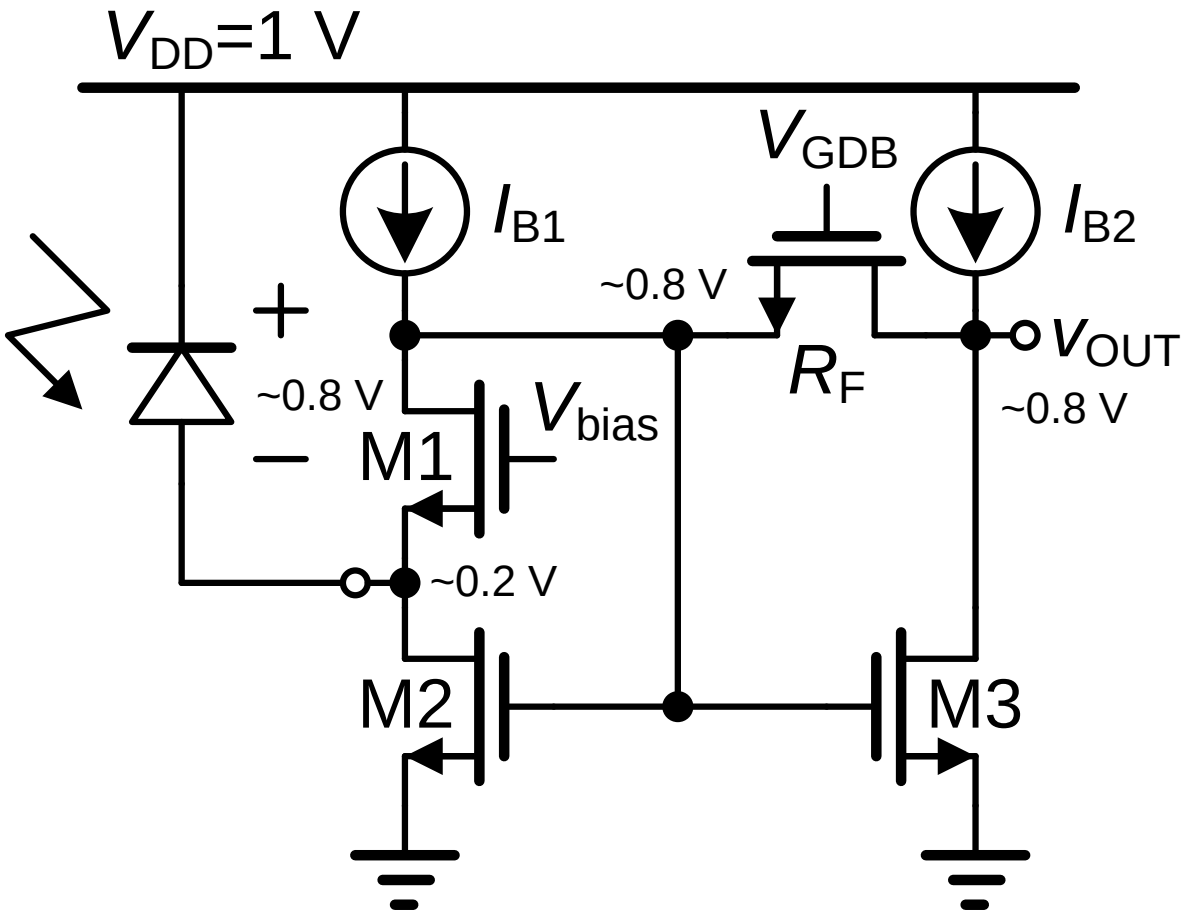




如果$R_F>1/g_{m1}$: $v_{out}=-R_F i_{in}$

Ref.: Phang, Johns, ISSCC 2001, 218-219

75 Mb/s CMOS光接收器



C_d = 1 pF

(40 μA)
2.4 kΩ
45 MHz

75 Mb/s
11 $pA_{RMS}/\sqrt{Hz}$

0.35 μm CMOS
1 V (1 mA)

Ref.: Phang, Johns, ISSCC 2001, 218-219