Feedback Transimpedance & Current Amplifiers

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- Shunt-series FB for Current amplifiers
- Transimpedance amplifiers for
  low noise and high frequencies

Input- & output impedances

$\frac{1}{H}$ = (Input \ Output)	Output: Shunt	Output: Series
	$R_{OUT} = \frac{R_{OUTOL}}{1+LG}$	$R_{OUT} = R_{OUTOL}(1+LG)$
Input: Shunt $R_{IN} = \frac{R_{INOL}}{1+LG}$	$\frac{v_{OUT}}{i_{IN}} = A_R$	$\frac{i_{OUT}}{i_{IN}} = A_I$
Input: Series $R_{IN} = R_{INOL}(1+LG)$	$\frac{v_{OUT}}{v_{IN}} = A_V$	$\frac{i_{OUT}}{v_{IN}} = A_G$

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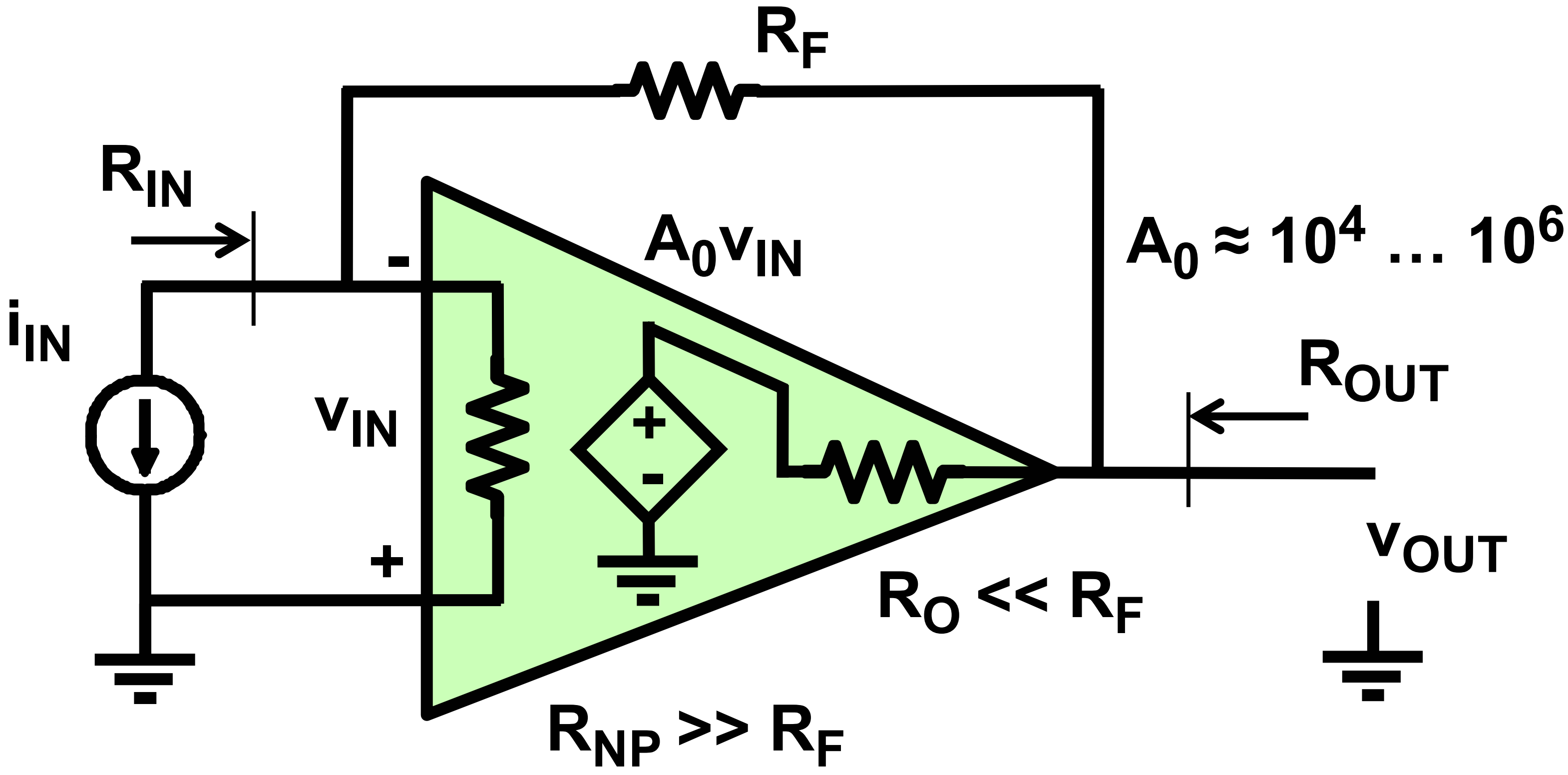
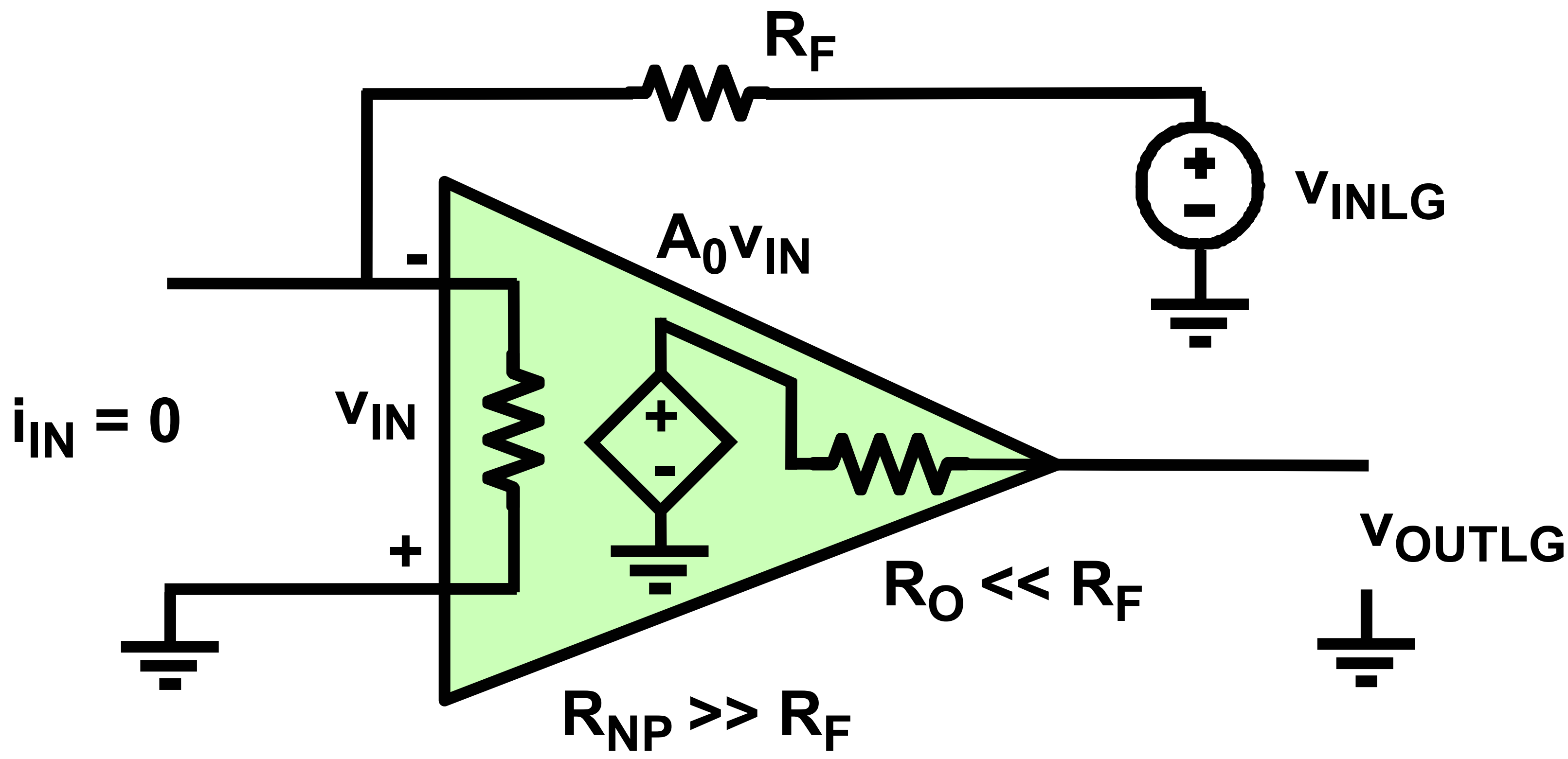
Shunt-shunt FB configuration



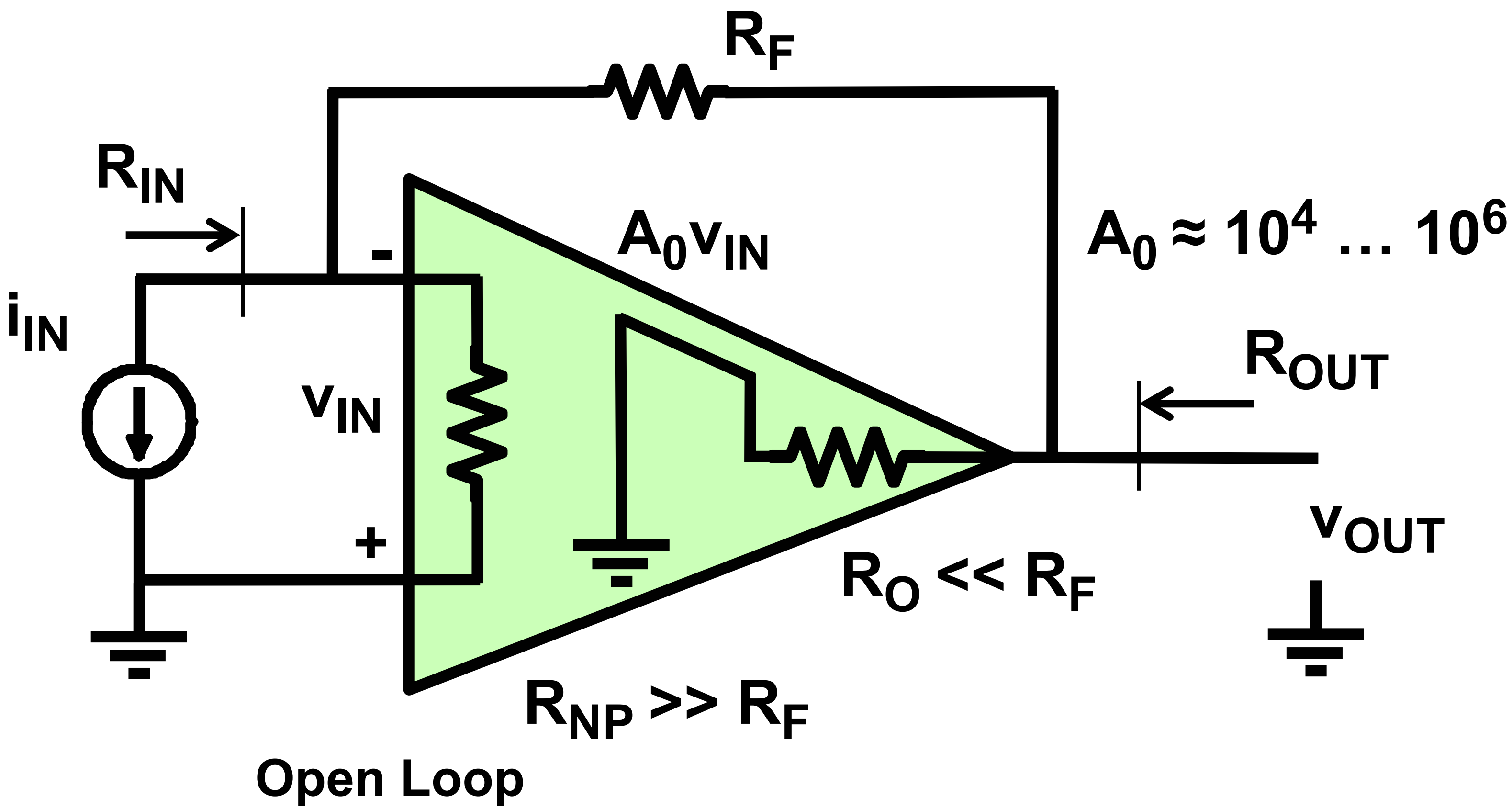
$$A_R = \frac{v_{OUT}}{i_{IN}} = R_F \qquad R_{IN} \approx 0 \qquad R_{OUT} \approx 0$$

Shunt-shunt FB : loop gain



$$LG = \frac{v_{OUTLG}}{v_{INLG}} \approx A_{vOL} \approx A_0 \approx 10^4 \ldots 10^6$$

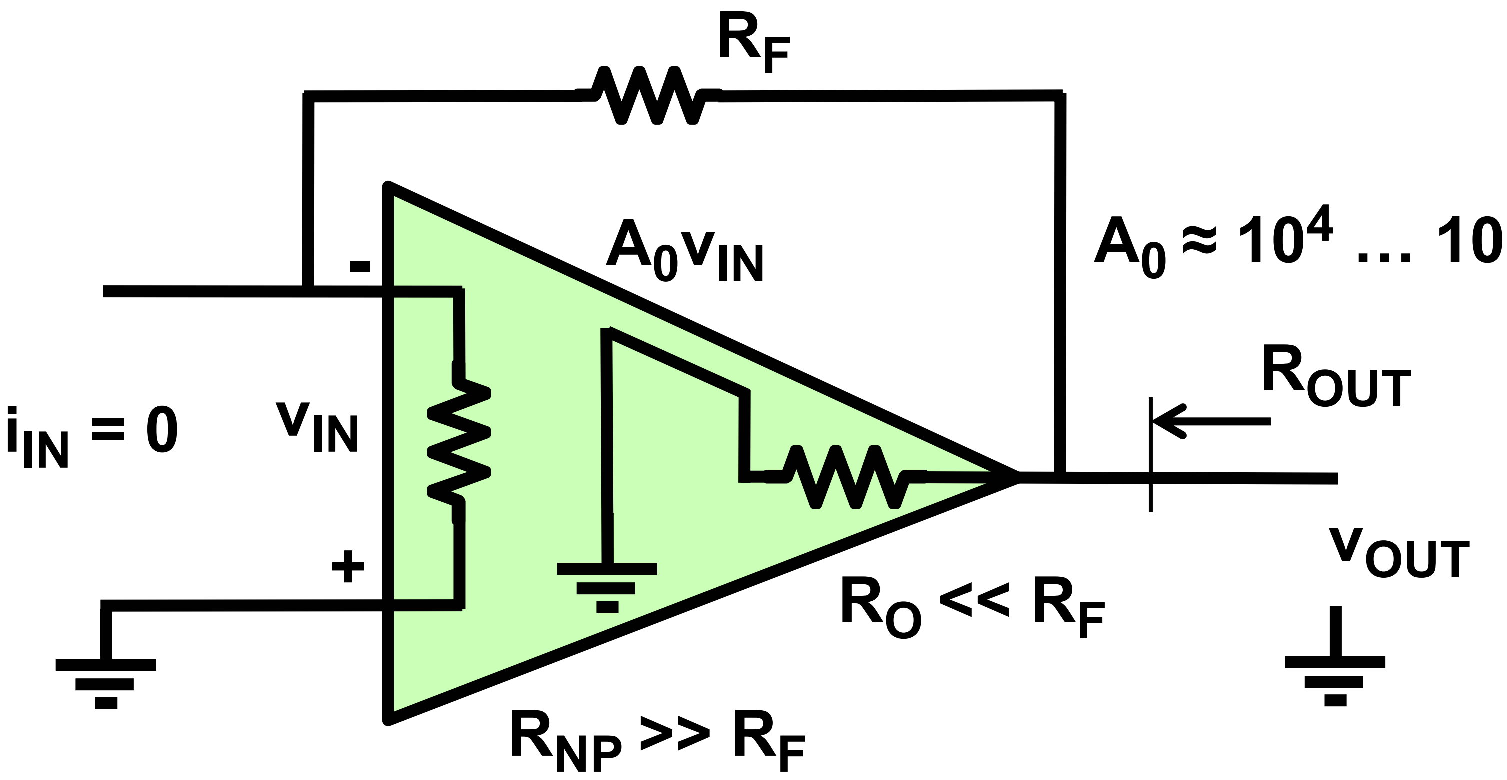
Shunt-shunt FB : input resistance



$$R_{IN} = \frac{v_{IN}}{i_{IN}} = \frac{R_{INOL}}{LG} \approx 0$$

$$R_{INOL} = R_{IN}\,(A_v = 0) = R_{NP} // (R_F + R_O)$$
$$\approx R_F$$

Shunt-shunt FB : output resistance



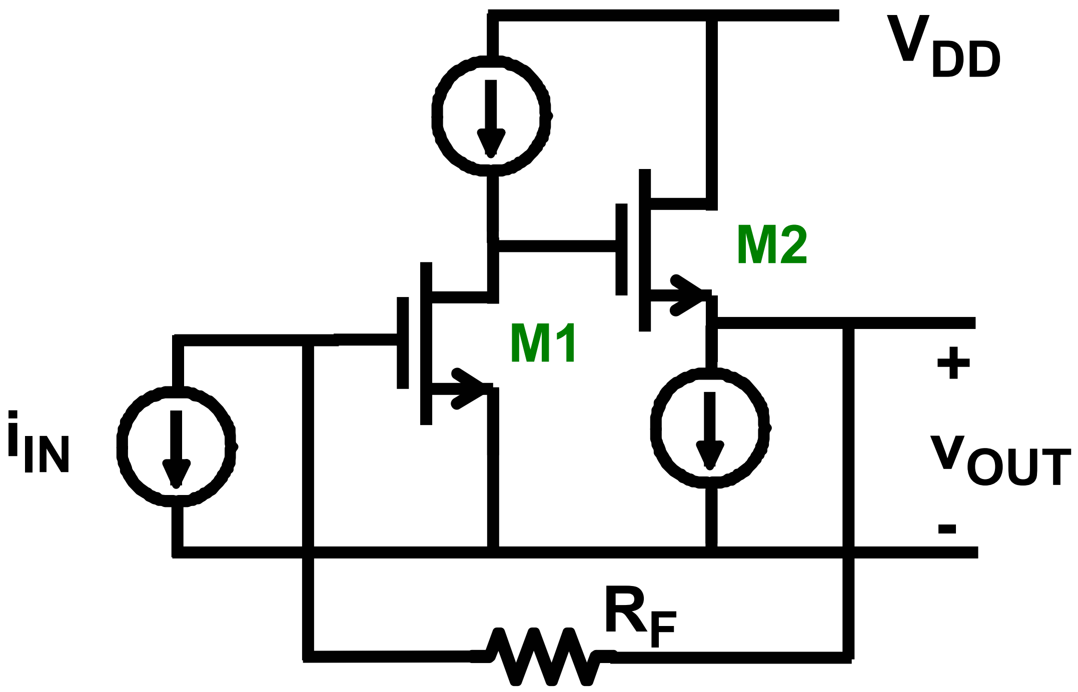
Open Loop

$$R_{OUT} = \frac{R_{OUTOL}}{LG} \approx 0$$

$R_{OUTOL} = R_{OUT}\ (A_v = 0)$

$= R_O//(R_F+R_{NP}) \approx R_O$

Shunt-shunt FB pair



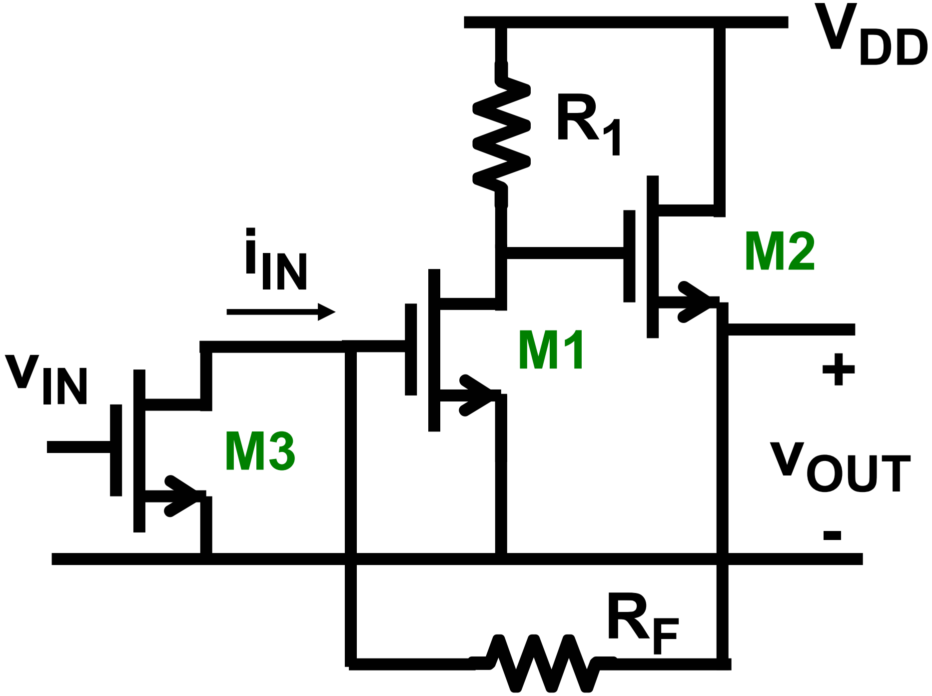
$$A_R = \frac{v_{OUT}}{i_{IN}} = R_F$$

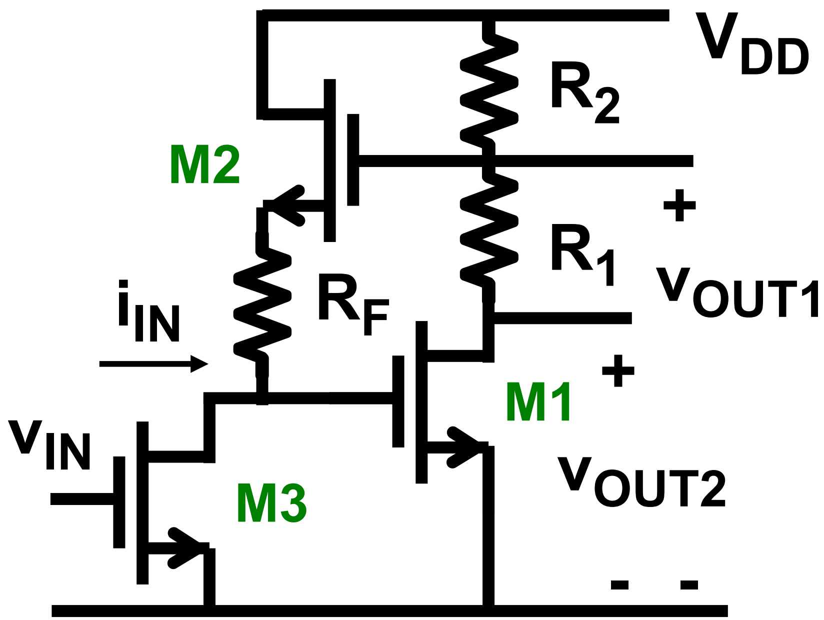
$$LG = g_{m1} r_{o1}$$

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

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

Shunt-shunt FB pair with resistors



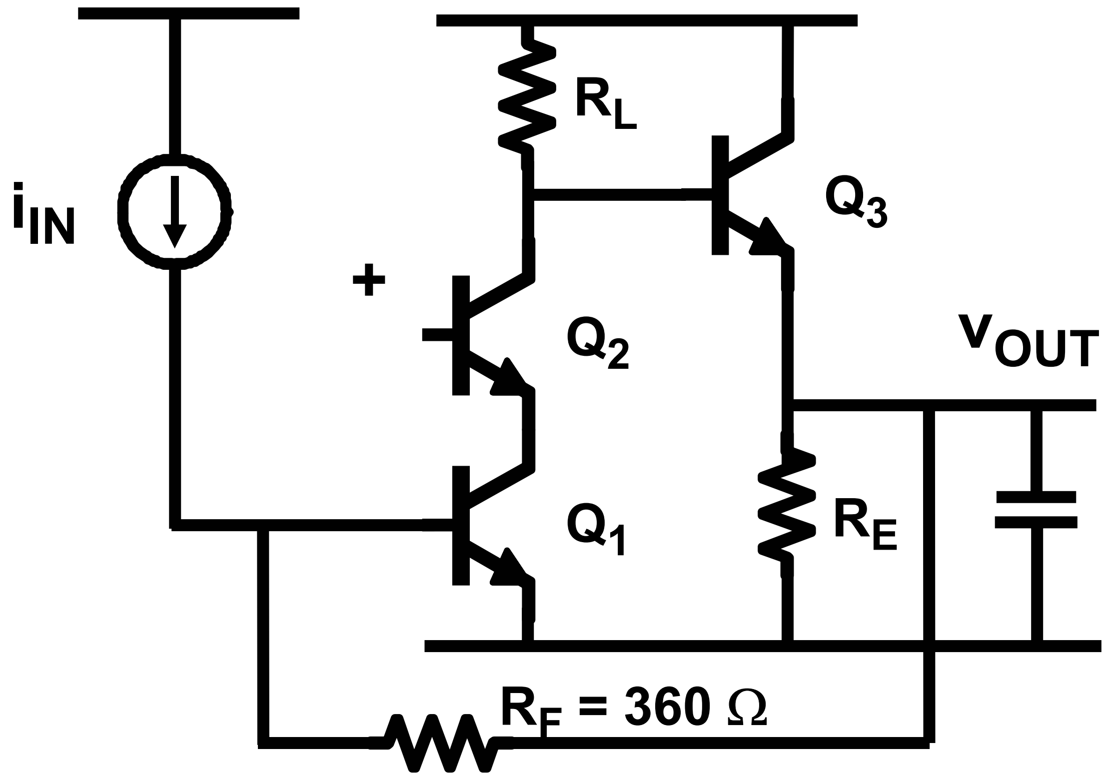


$$A_R = \frac{v_{OUT}}{i_{IN}} = R_F$$

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

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

Current detector with voltage amp.

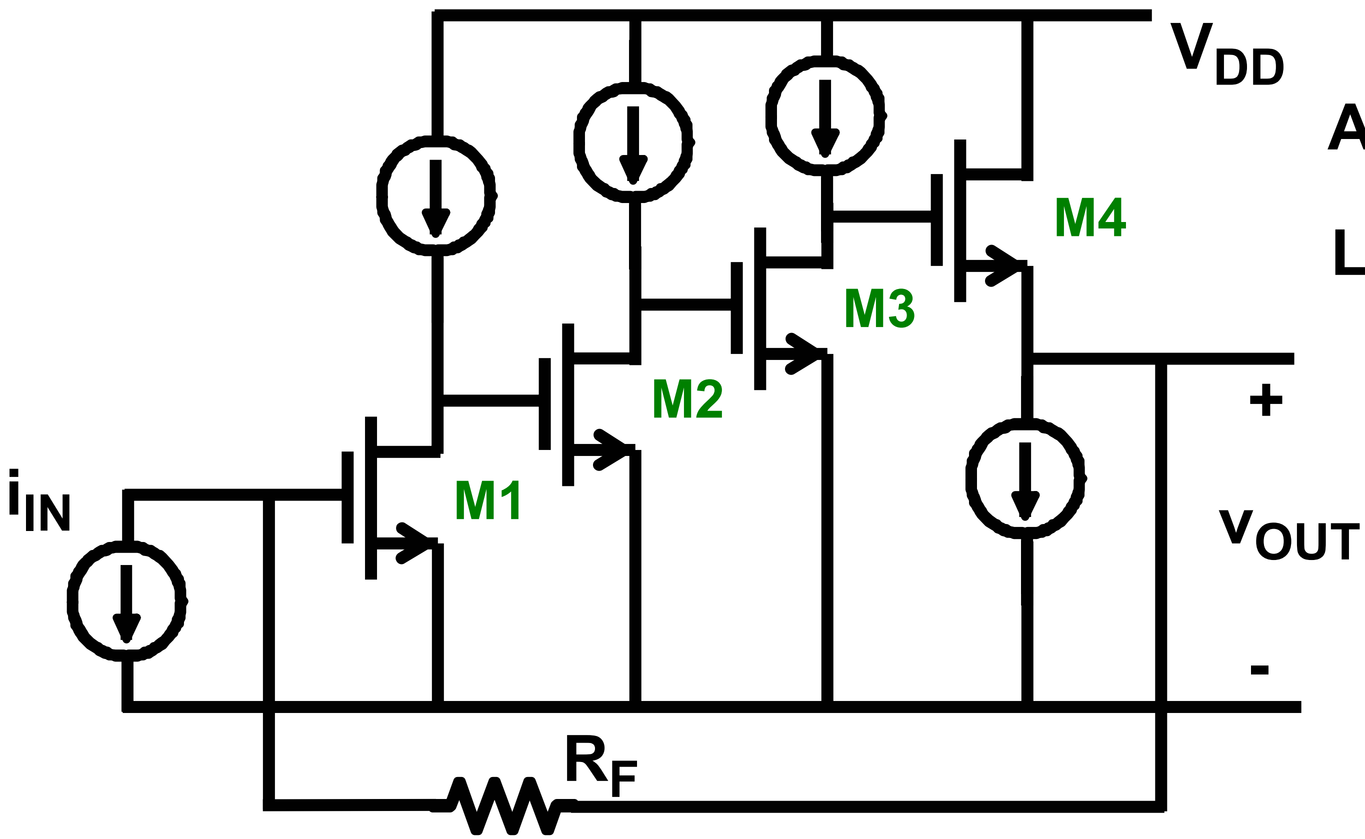


$v_{OUT} = R_F\, i_{IN}$

f_T = 40 GHz r_B = 20 Ω BW = 10 GHz I_{TOT} = 10 mA

Ref.Baureis, JSSC June 1993, 701-706

Shunt-shunt FB triple



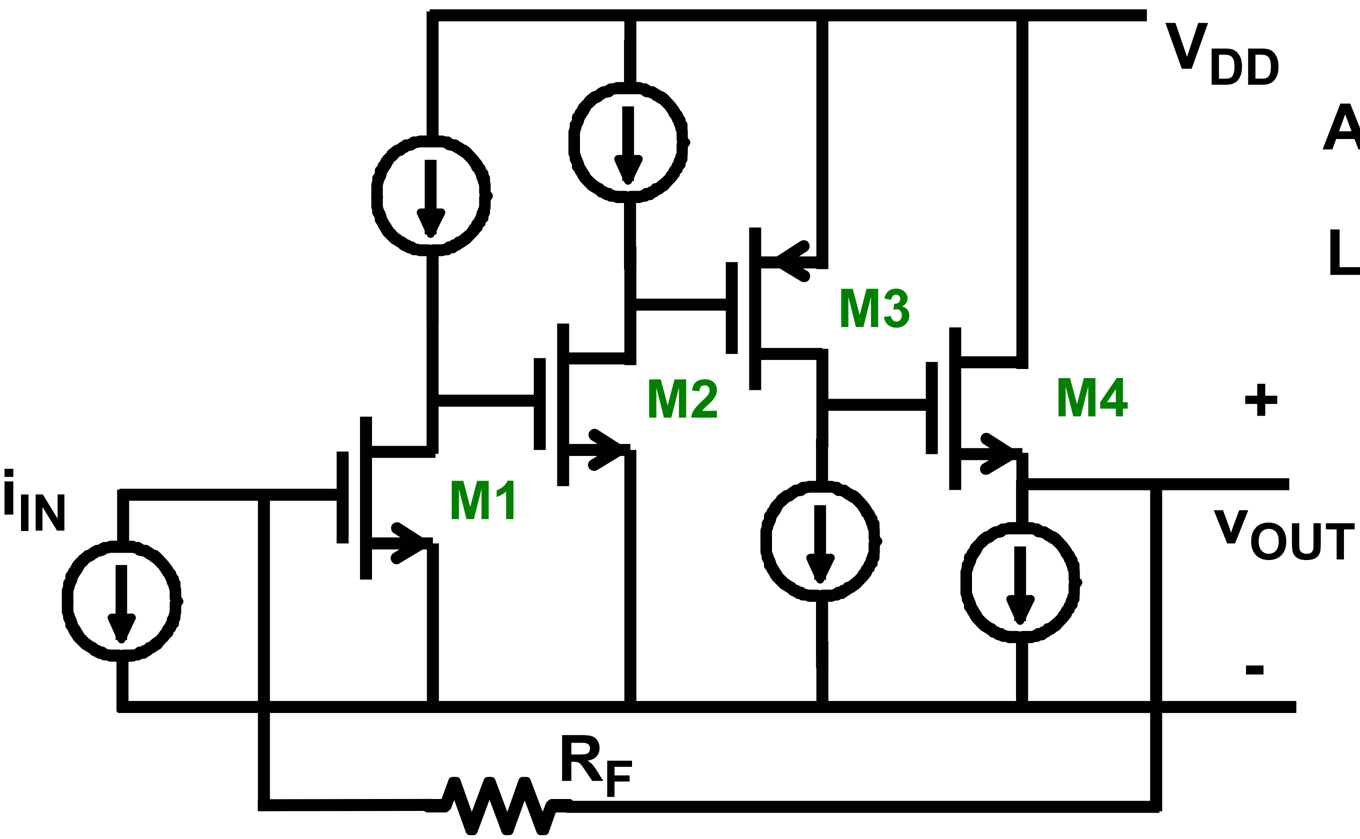
$A_R = R_F$

$LG = A_{v1}A_{v2}A_{v3}$

$A_{vi} = g_{mi}r_{oi}$

$R_{IN} = \frac{R_F}{LG} \approx 0$ $\quad R_{OUT} = \frac{1/g_{m4}}{LG} \approx 0$

Shunt-shunt FB triple: easier biasing



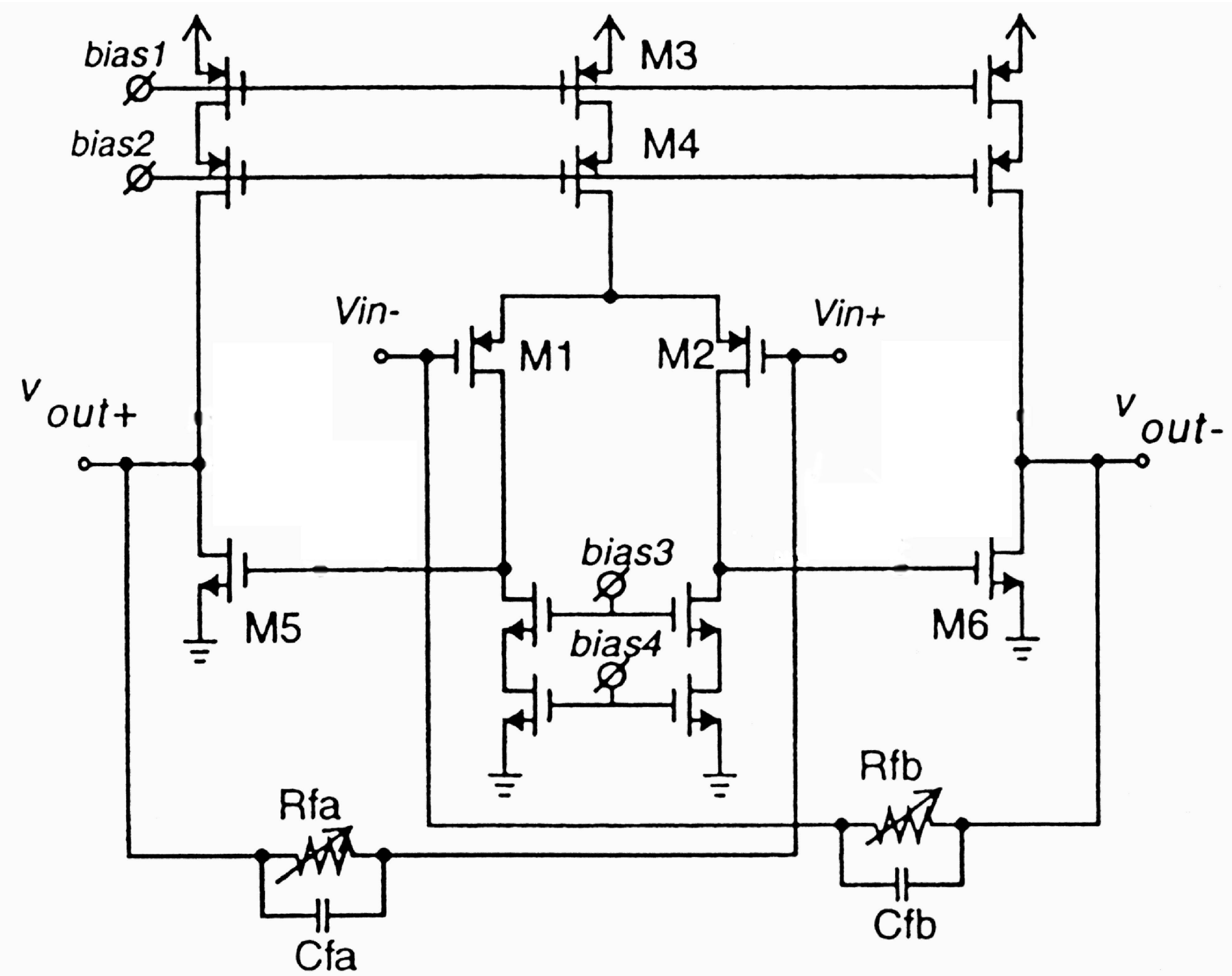
$A_R = R_F$

$LG = A_{v1}A_{v2}A_{v3}$

$A_{vi} = g_{mi}r_{oi}$

$R_{IN} = \frac{R_F}{LG} \approx 0$ $\quad R_{OUT} = \frac{1/g_{m4}}{LG} \approx 0$

CMOS preamplifier for optical communications



Two stages
possible
if fully differential !

20 kΩ … 500 Ω

tracking
of R1 & Rf

Ref.Phang, Johns,
CAS-II July 1999

Differential shunt-shunt FB pair

$A_R = R_F$

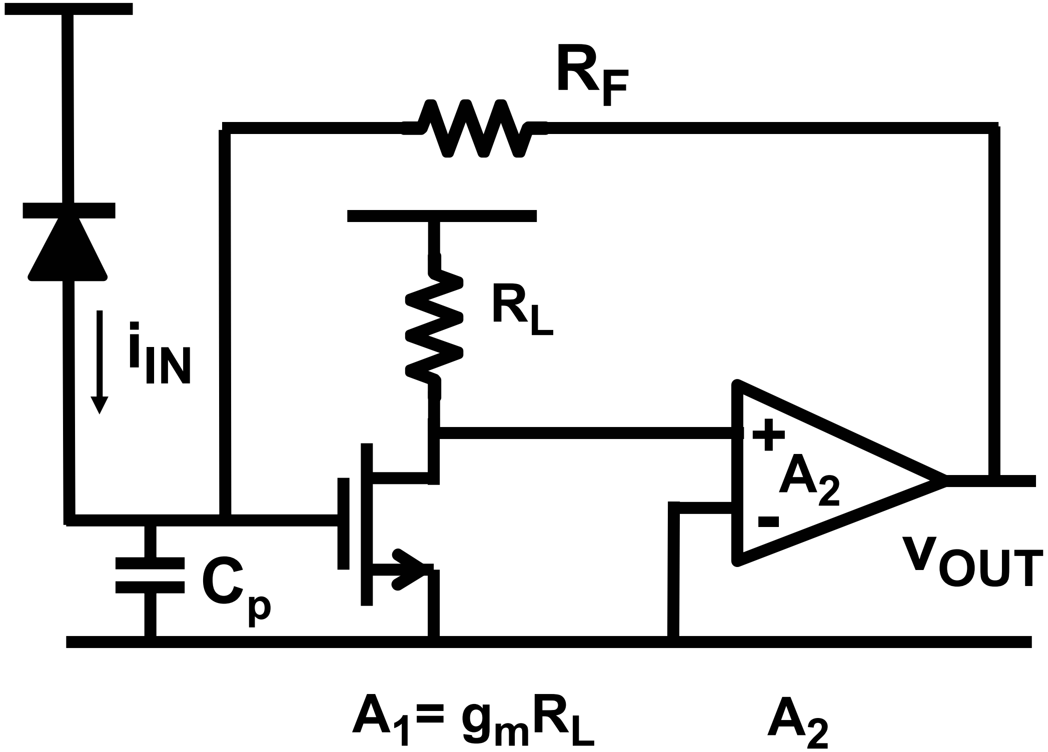
$LG = A_{v1}A_{v2}$

$A_{v1} = g_{m1}r_{o1}$

$A_{v2} = g_{m2}r_{o2}$

$R_{IN} = \frac{2R_F}{LG} \approx 0 \qquad R_{OUT} = \frac{2/g_{m3}}{LG} \approx 0$

Current detector with voltage amplifier



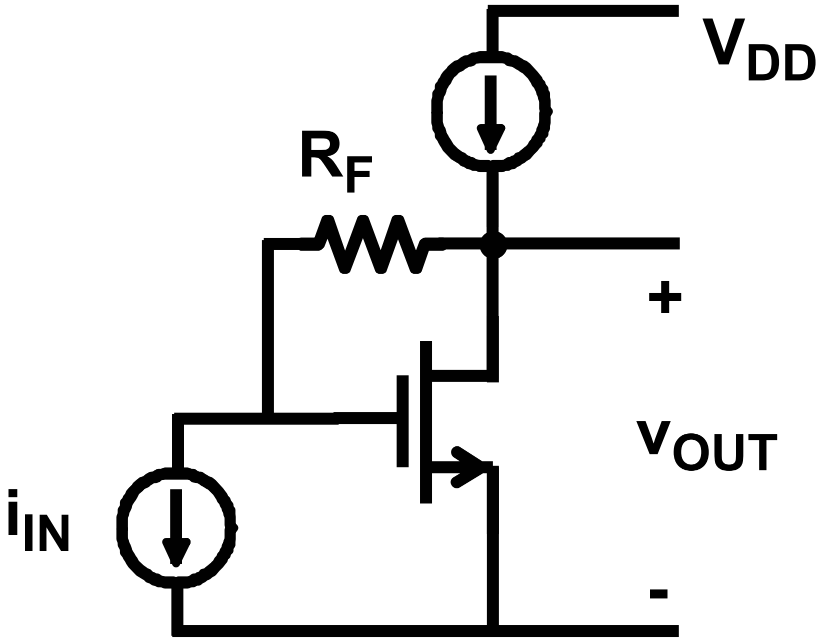
$$R_{IN} = \frac{v_{IN}}{i_{IN}} = \frac{R_F}{A_1A_2}$$

$$A_R = \frac{v_{OUT}}{i_{IN}} = R_F$$

$$LG = A_1A_2$$

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

Single MOST with shunt-shunt FB



$A_R = R_F$ (if $>> 1/g_m$)

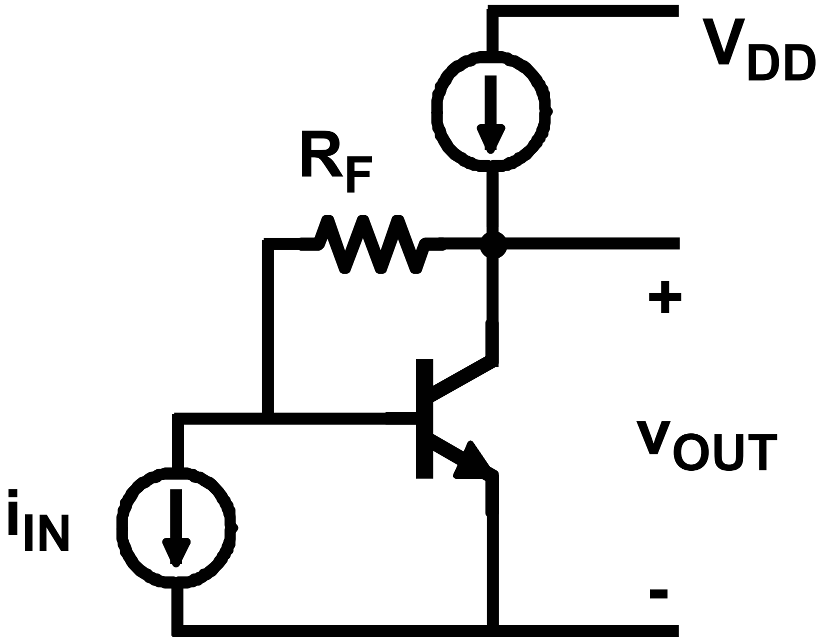
$LG = g_m r_o$

$R_{IN} = \dfrac{R_F + r_o}{LG} \approx 0$?

$R_{OUT} = \dfrac{r_o}{LG} \approx 0$?

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

Single bipolar transistor with shunt-shunt FB



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

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

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

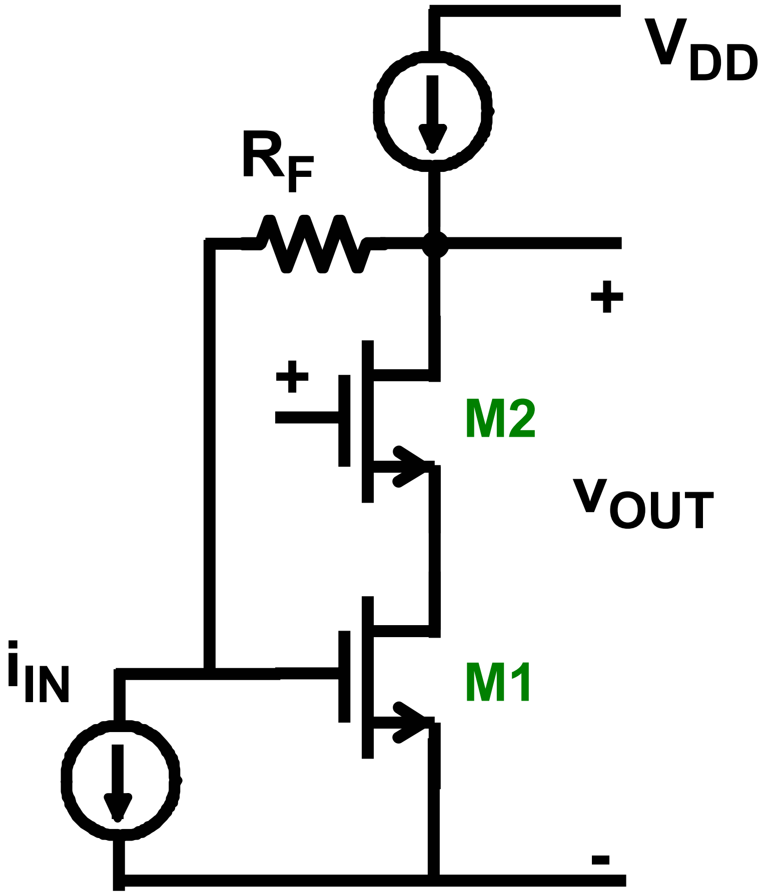
$$R_{OUT} = \frac{r_o \,//\, (R_F + r_\pi)}{LG} \approx 0 \ ?$$

Far from ideal !!

Output loading : $R_F + r_\pi \approx r_o$

reduces the LG !!

Cascode with shunt-shunt FB



$$A_R = R_F$$

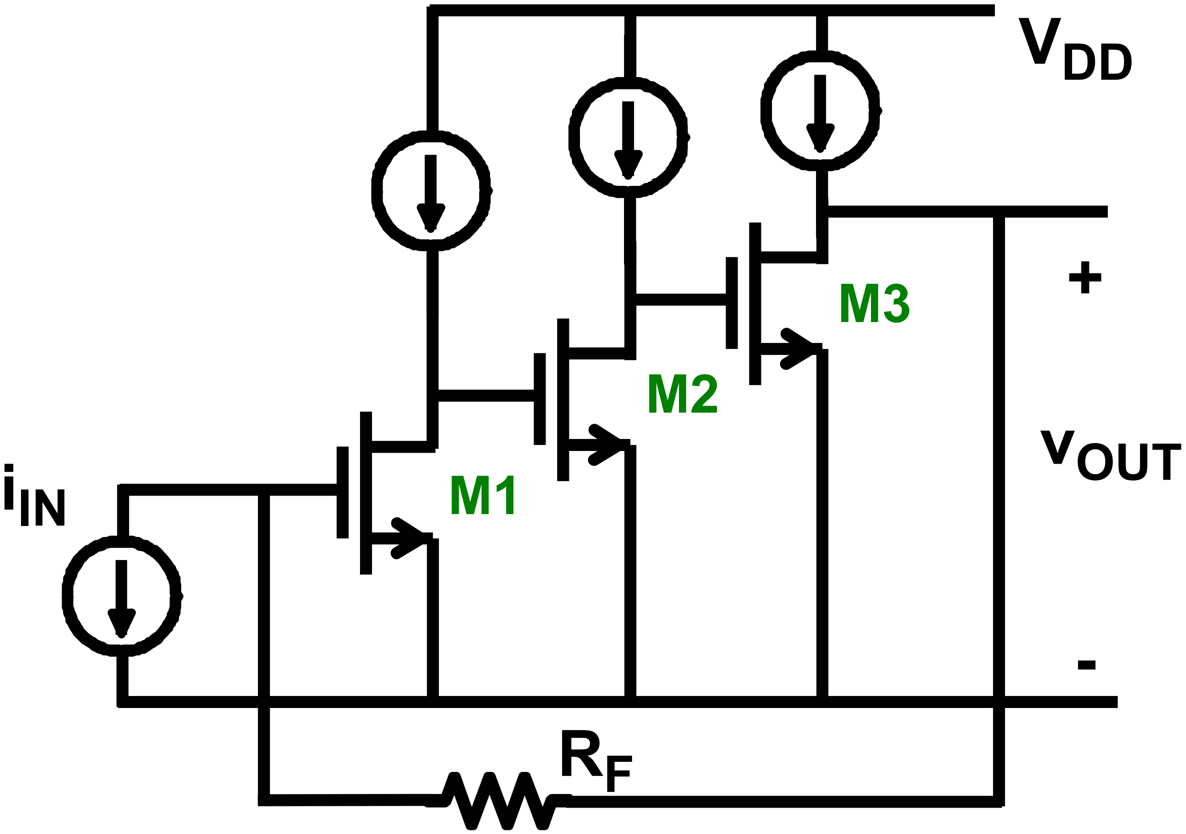
$$LG = g_{m1} r_{o1}\ g_{m2} r_{o2}$$

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

$$r_{OUT} = r_{o1} g_{m2} r_{o2}$$

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

MOST Shunt-shunt FB triple



$$A_R = R_F$$

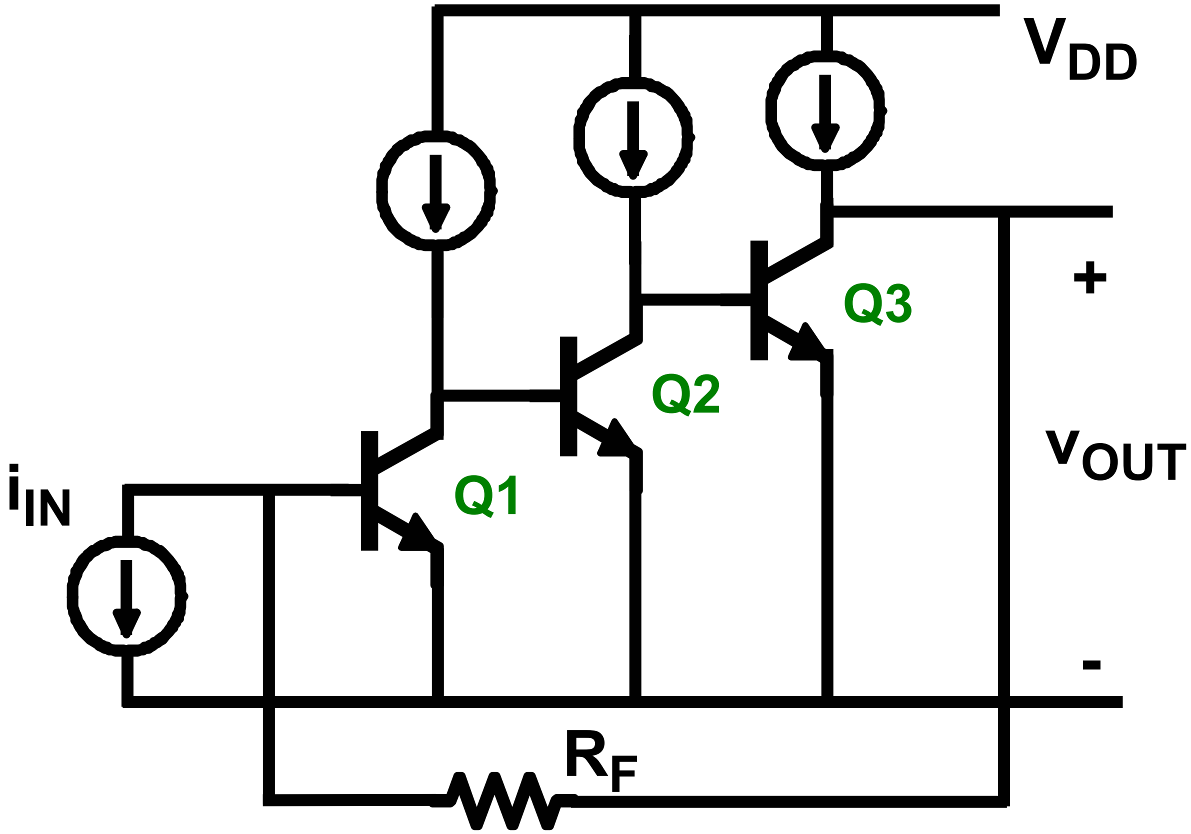
$$LG = A_{v1}A_{v2}A_{v3}$$

$$A_{vi} = g_{mi}r_{oi}$$

$$R_{IN} = \frac{R_F + r_{o3}}{LG} \approx 0$$

$$R_{OUT} = \frac{r_{o3}}{LG} \approx 0$$

Bipolar Transistor Shunt-shunt FB triple



$$A_R = R_F$$

$$LG = A_{v1}A_{v2}A_{v3}$$

$$A_{v1} = g_{m1}(r_{o1}//r_{\pi 2})$$

$$A_{v2} = g_{m2}(r_{o2}//r_{\pi 3})$$

$$A_{v3} = g_{m3}\,R_{OUTOL}$$

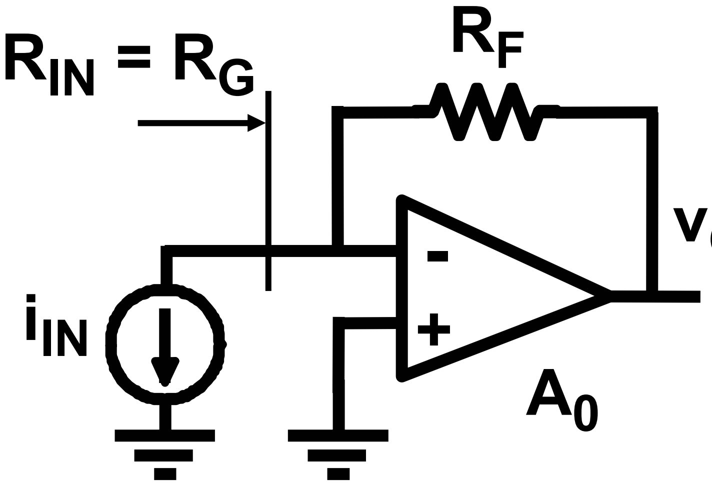
$$R_{OUTOL} = r_{o3}//(R_F + r_{\pi 1})$$

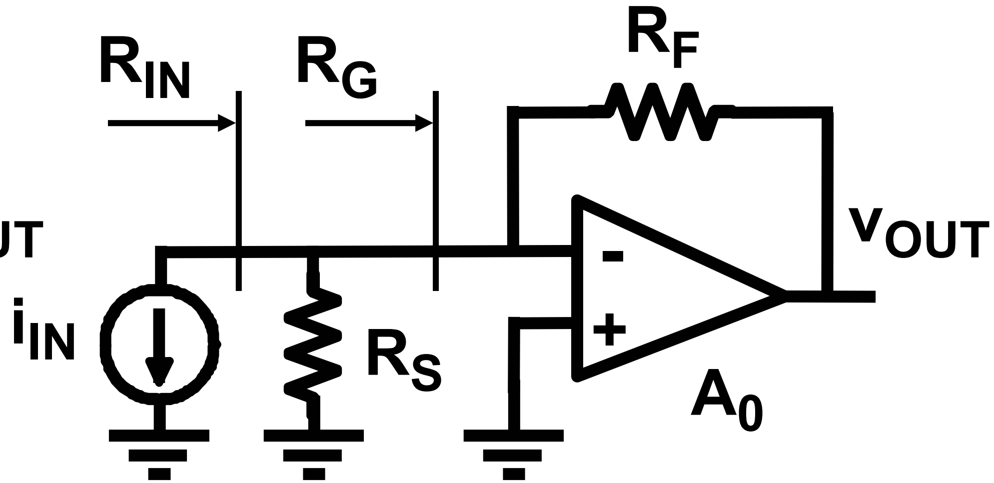
$$R_{OUT} = \frac{R_{OUTOL}}{LG} \approx 0$$

Output loading : $R_F + r_{\pi 3} \approx r_{o3}$ reduces the LG !!

$$R_{IN} = \frac{(R_F + r_{o3})\,//r_{\pi 1}}{LG} \approx 0$$

Shunt-shunt FB with non-ideal current source





$A_R = R_F$

$LG = A_0$

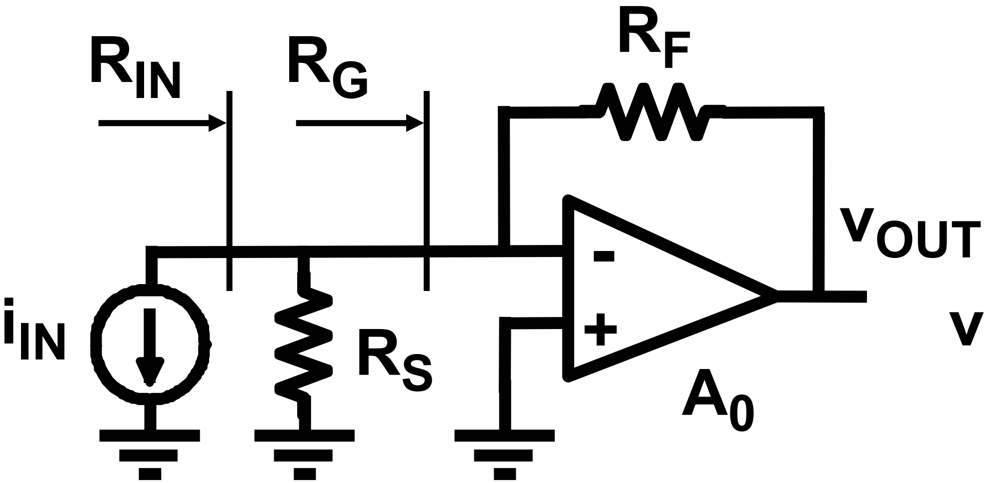
$$R_{IN} = \frac{R_F}{A_0}$$

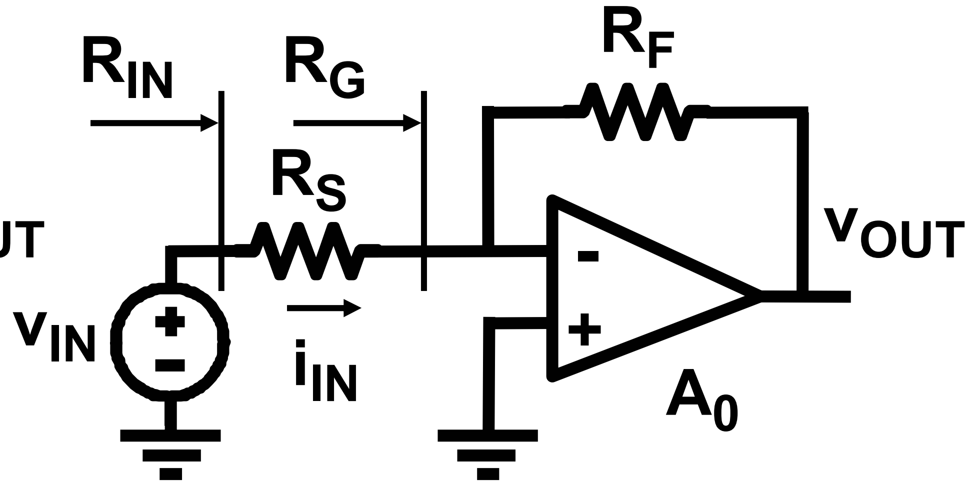
$A_R = R_F$ if $R_S > \frac{R_F}{A_0}$

$LG = A_0$

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

Shunt-shunt FB with voltage source





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

$LG = A_0$

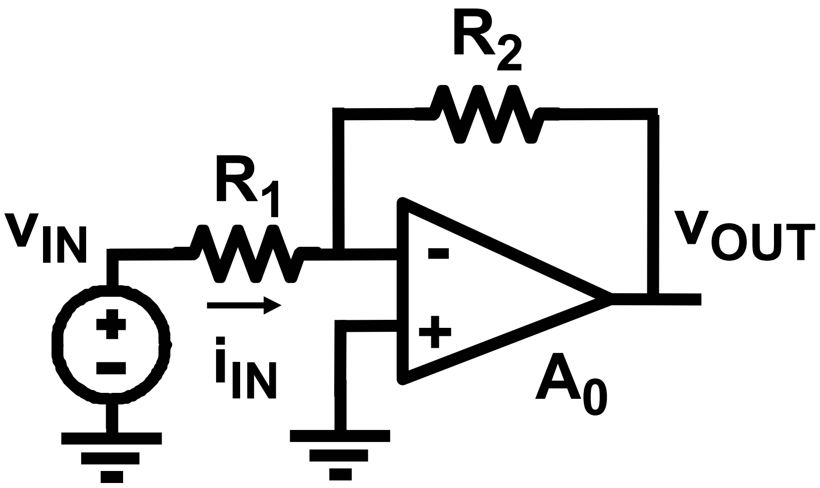
$R_G = \dfrac{R_F}{A_0}$ $R_{IN} = R_G // R_S$

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

$LG = A_0$

$R_G = \dfrac{R_F}{A_0}$ $R_{IN} = R_G + R_S$

Shunt-shunt feedback : Gain and R_{OUT}



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

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

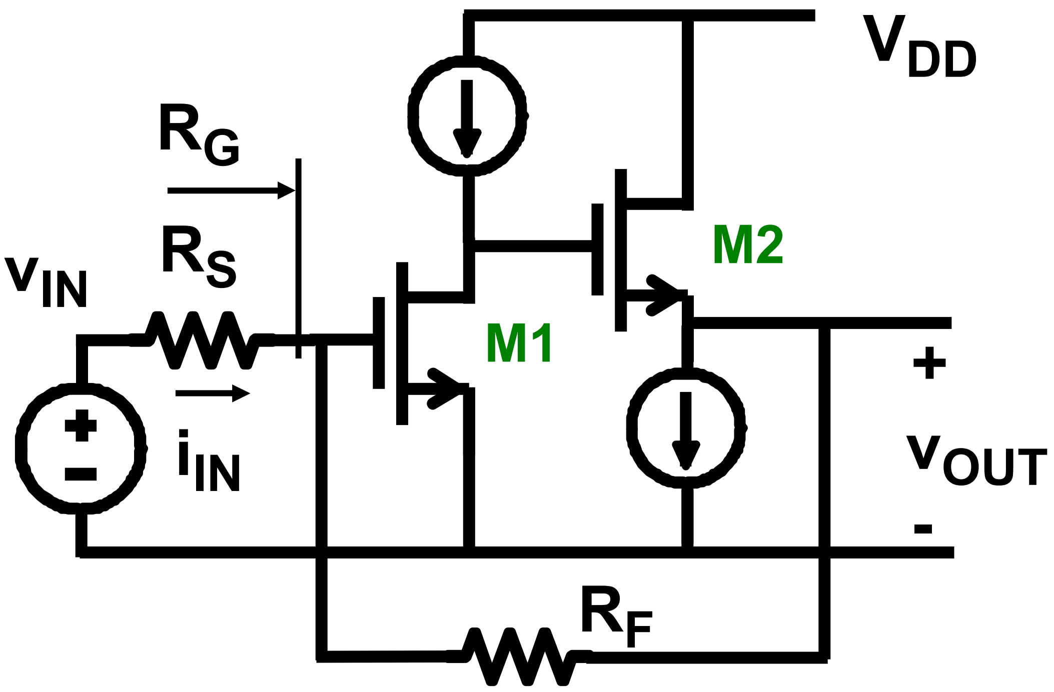
$$\frac{v_{OUT}}{v_{IN}} = \frac{v_{OUT}}{i_{IN}} \frac{i_{IN}}{v_{IN}}$$

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

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

$$R_{OUT} = \frac{R_{OUTOL}}{LG}$$

Shunt-shunt FB pair with with voltage source



$A_R = R_F \quad A_v = -\frac{R_F}{R_S}$

$LG = g_{m1} r_{o1}$

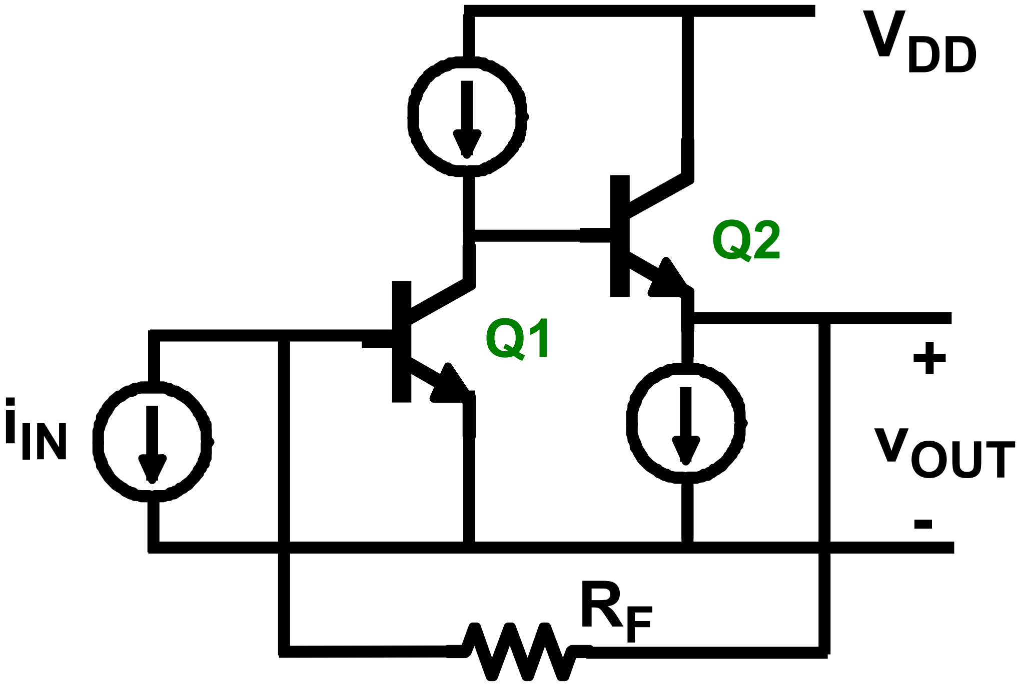
$R_{IN} = R_S + R_G$

$R_G = \frac{R_F}{LG} = \frac{R_F}{g_{m1} r_{o1}} \approx 0$

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

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

Shunt-shunt FB pair with input loading



$$A_R = R_F$$

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

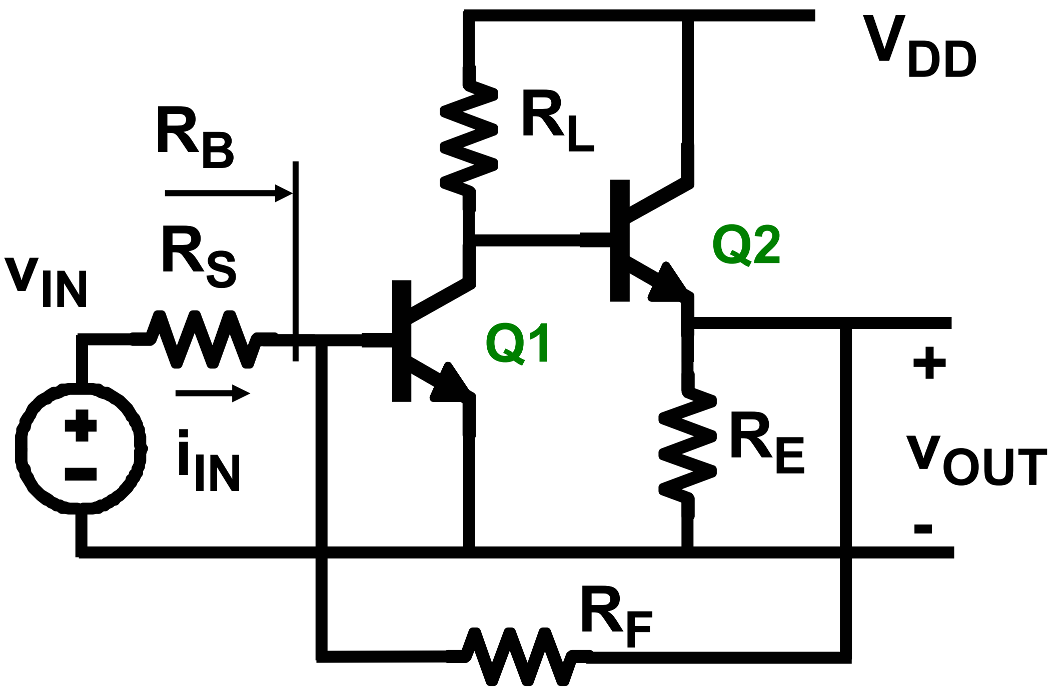
$$R_{IN} = \frac{R_F \,//\, r_{\pi 1}}{LG} = \frac{R_F}{g_{m1} r_{o1}} \approx 0$$

$$R_{OUT} = \frac{R_{OUTOL}}{LG} \approx 0$$

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

Input loading : $R_F \approx r_{\pi 1}$

Shunt-shunt FB pair with voltage source



$$A_R = -R_F \qquad A_v = -\frac{R_F}{R_S}$$

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

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

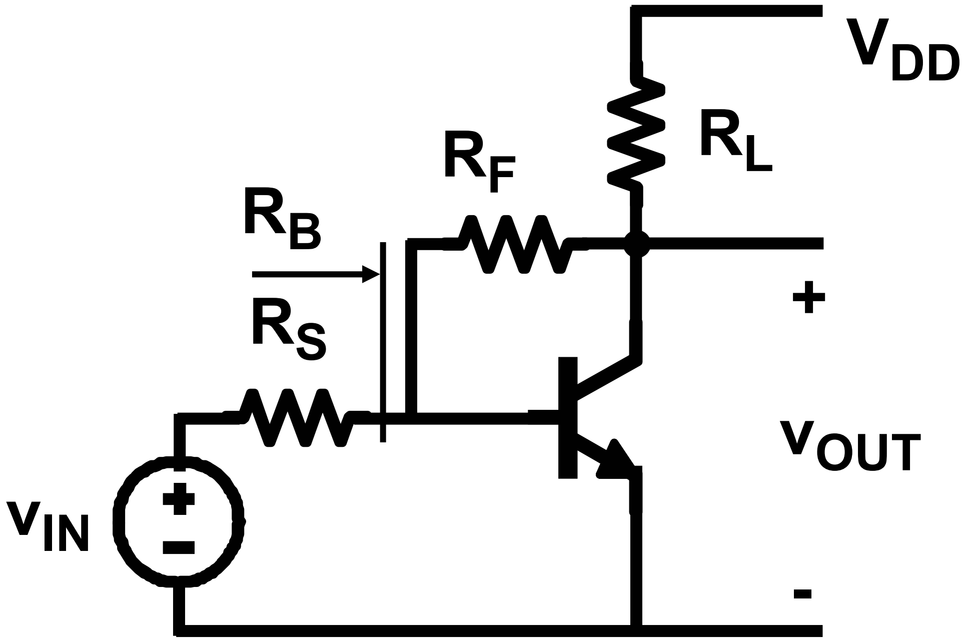
$$R_{IN} = R_S + R_B$$

Input loading :

$R_F \approx r_{\pi 1}$

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

Non-ideal single-transistor shunt-shunt FB



$A_R \approx R_F \qquad A_v \approx -\frac{R_F}{R_S}$

$LG \approx g_m r_{oLF}$

$R_{IN} = R_S + R_B$

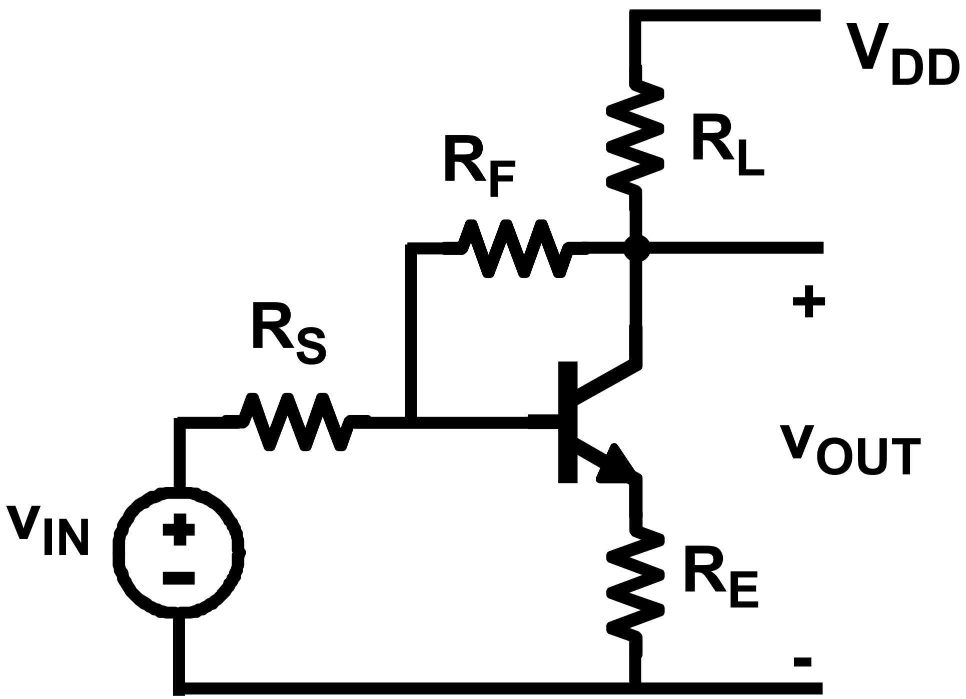
$$R_B \approx \frac{r_\pi // (R_F + r_{oL})}{LG} \approx 0$$

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

Output loading : $R_F \approx r_{oL}$ $\quad r_{oL} = r_o // R_L \quad r_{oLF} = r_o // R_L // R_F$

Input loading : $R_F \approx r_\pi$

Non-ideal single-transistor Feedback



$A_R = R_F$ $\quad A_v = -\dfrac{R_F}{R_S}$

$LG = \ ?$

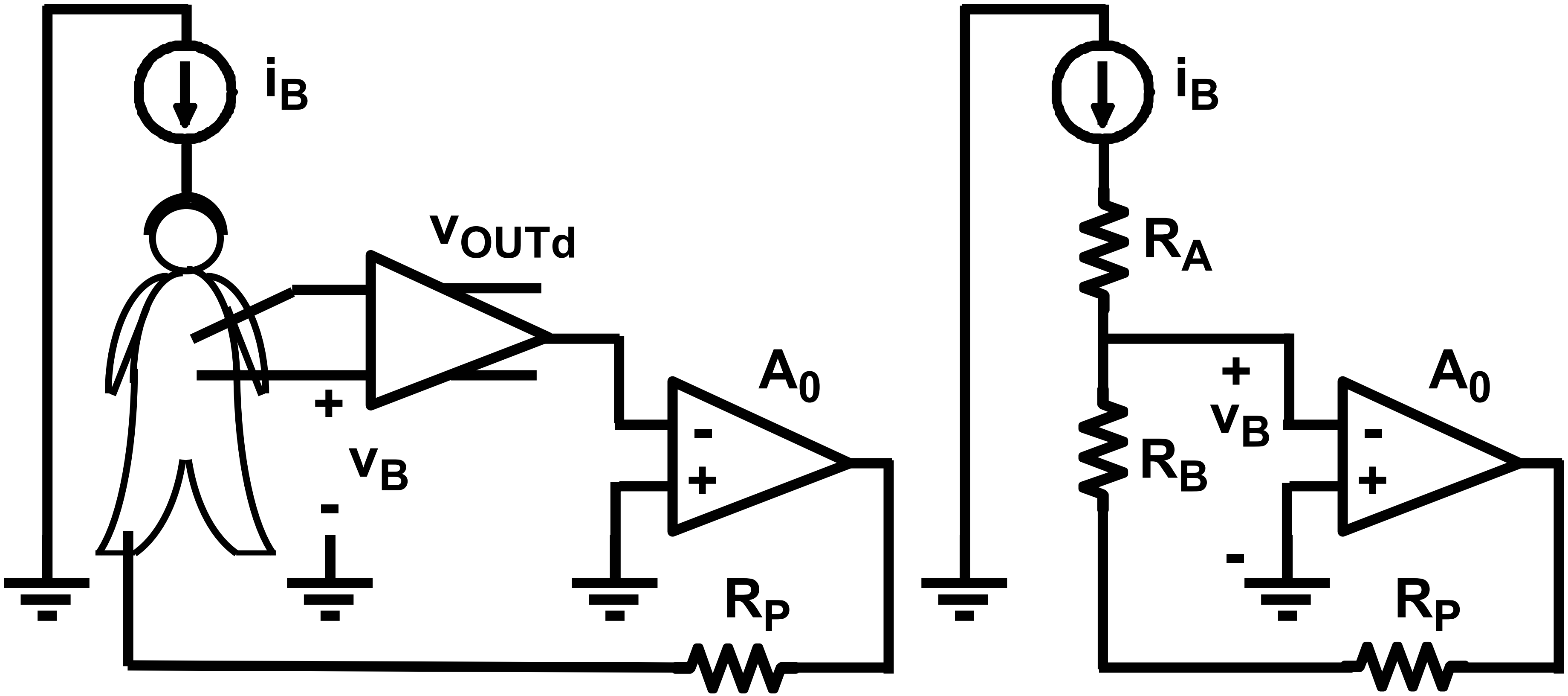
$R_{IN} = ?$

$R_{OUT} = ?$

Output loading : $R_F \approx r_{oL}$ $\quad r_{oL} = r_o // R_L$

Input loading : $R_F \approx r_\pi$

Shunt-shunt feedback in Right-leg drive



$i_B \approx 10\ \mu A_{RMS}$

for 220 V_{RMS} (50 Hz) through 150 pF

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

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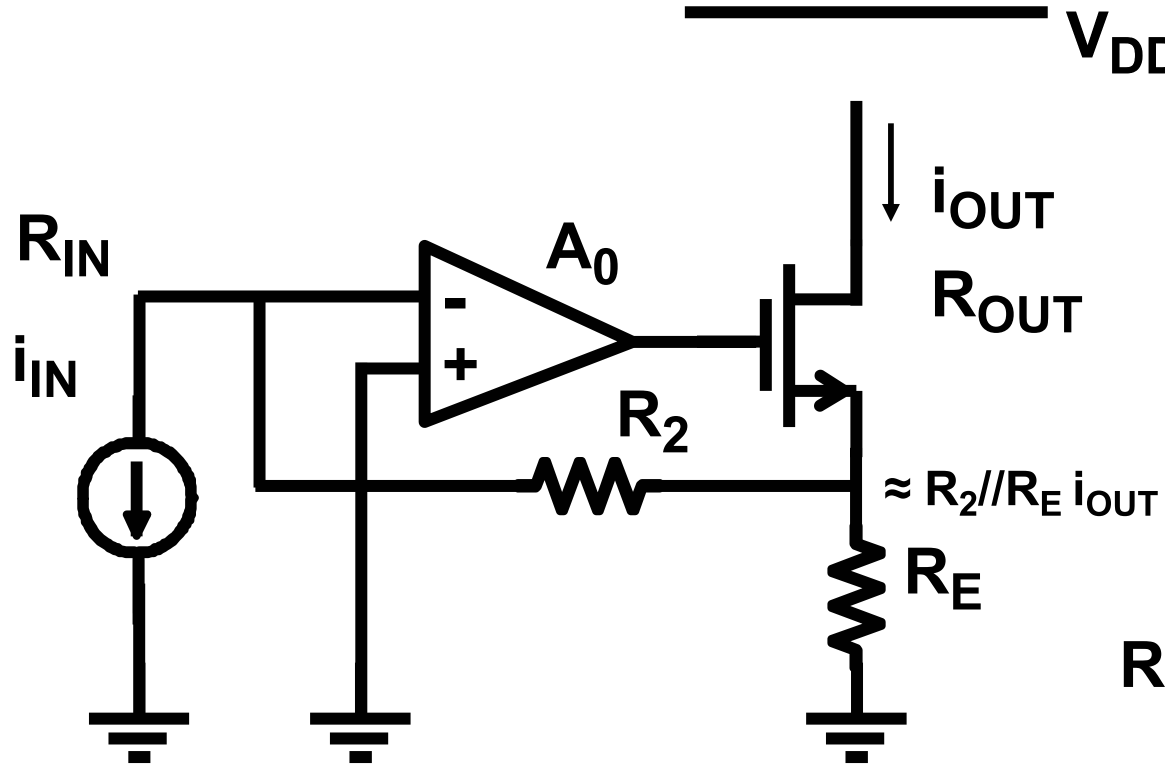
Shunt-series feedback : Gain, RIN & ROUT



$LG = A_0$

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

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

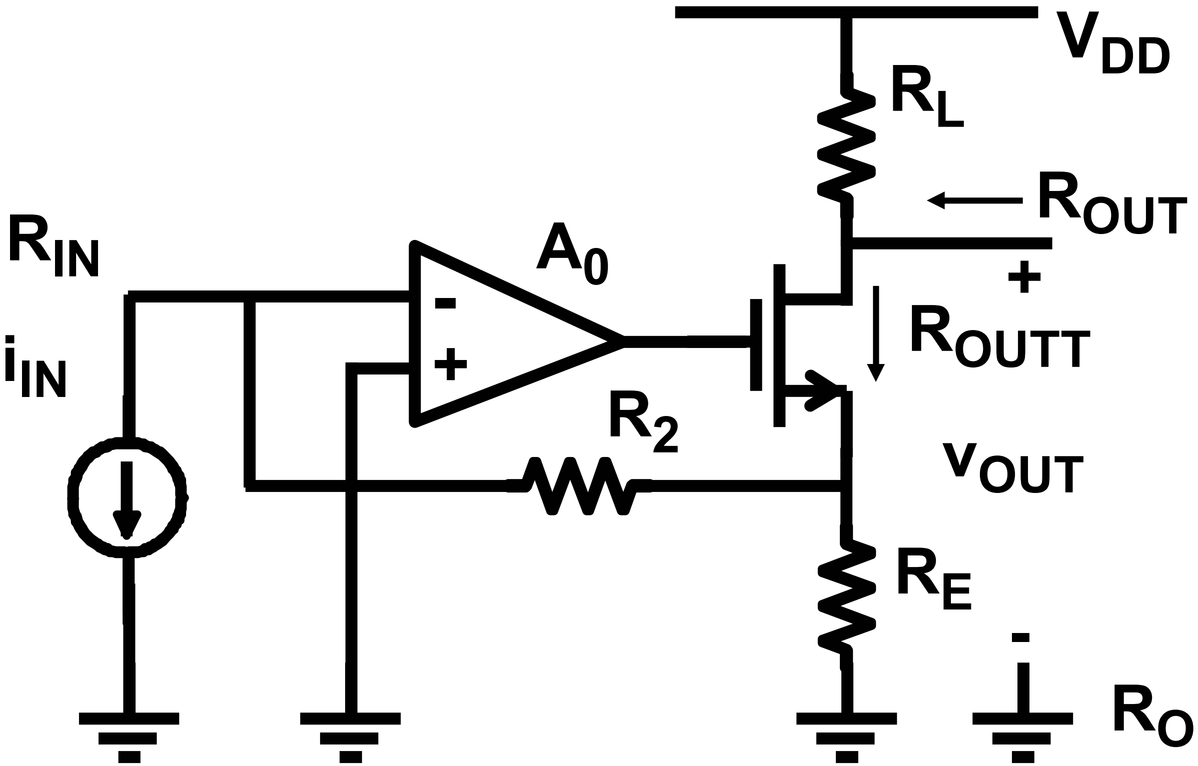
$R_{OUTOL} = r_o\,(1 + g_m R_E)$

$R_{OUT} = R_{OUTOL}\,LG \approx \infty$

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

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

Shunt-series feedback with load RL



$LG = A_0$

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

$A_R = A_I R_L$

$R_{IN} = \frac{R_2}{LG} \approx 0$

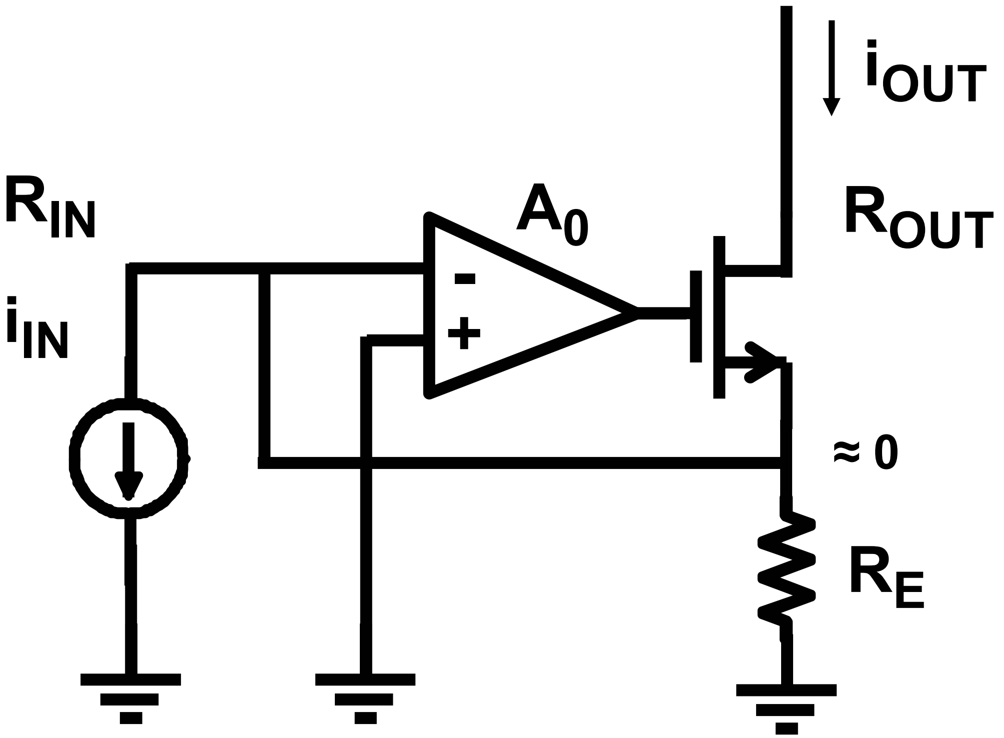
$R_{OUT} = R_{OUTT} // R_L \approx R_L$

$R_{OUTT} = R_{OUTTOL}\, LG \approx \infty$

$R_{OUTTOL} = r_o\,(1 + g_m R_E)$

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

Ideal current buffer



$R_E > 1/g_m$

$A_I = 1$

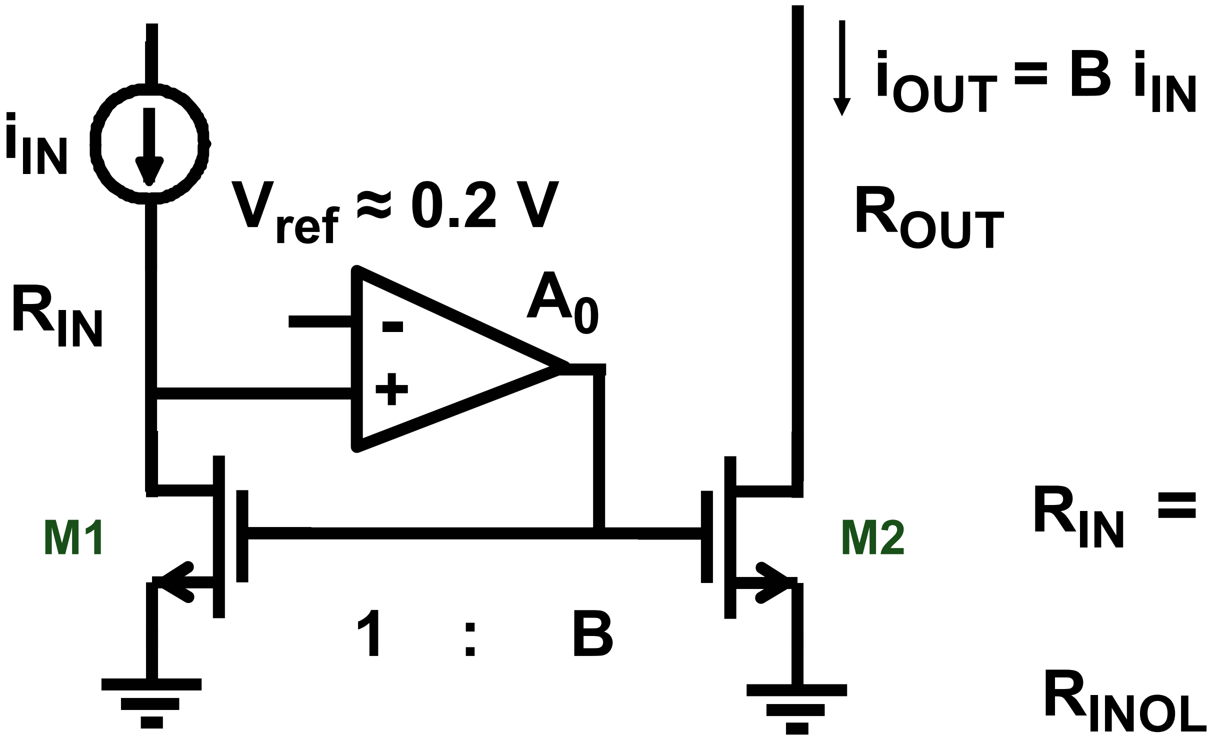
$LG = A_0$

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

$$R_{OUTOL} = r_o\,(1 + g_m R_E)$$

$$R_{OUT} = R_{OUTOL}\,LG \approx \infty$$

Ideal current mirror



$A_I = B$

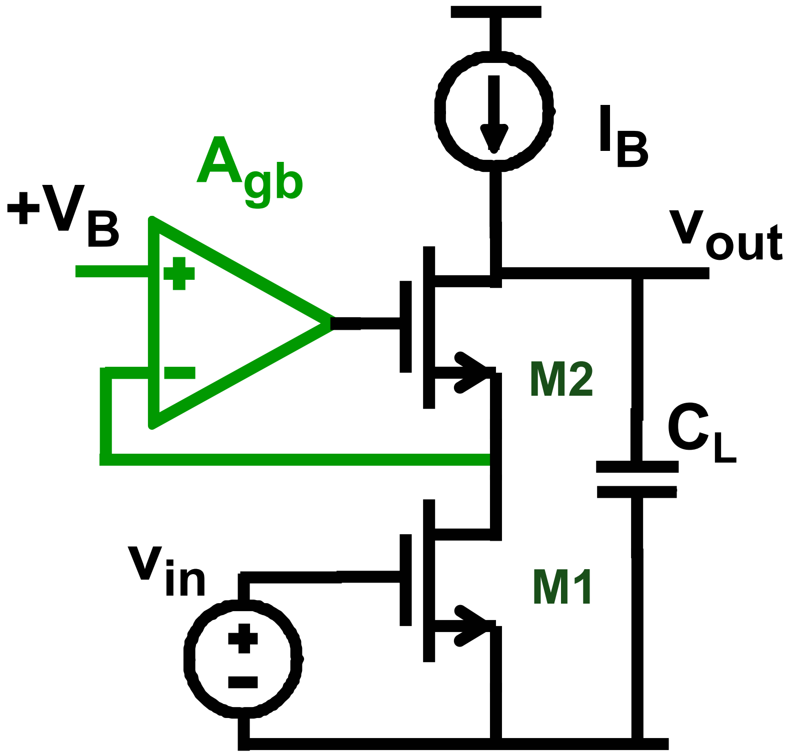
$LG = g_{m1} r_{o1} A_0$

$$R_{IN} = \frac{R_{INOL}}{LG} = \frac{1}{g_{m1} A_0} \approx 0$$

$R_{INOL} = r_{o1}$

$R_{OUT} = r_{o2}$

Gain boosting



$$LG = A_{gb}$$

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

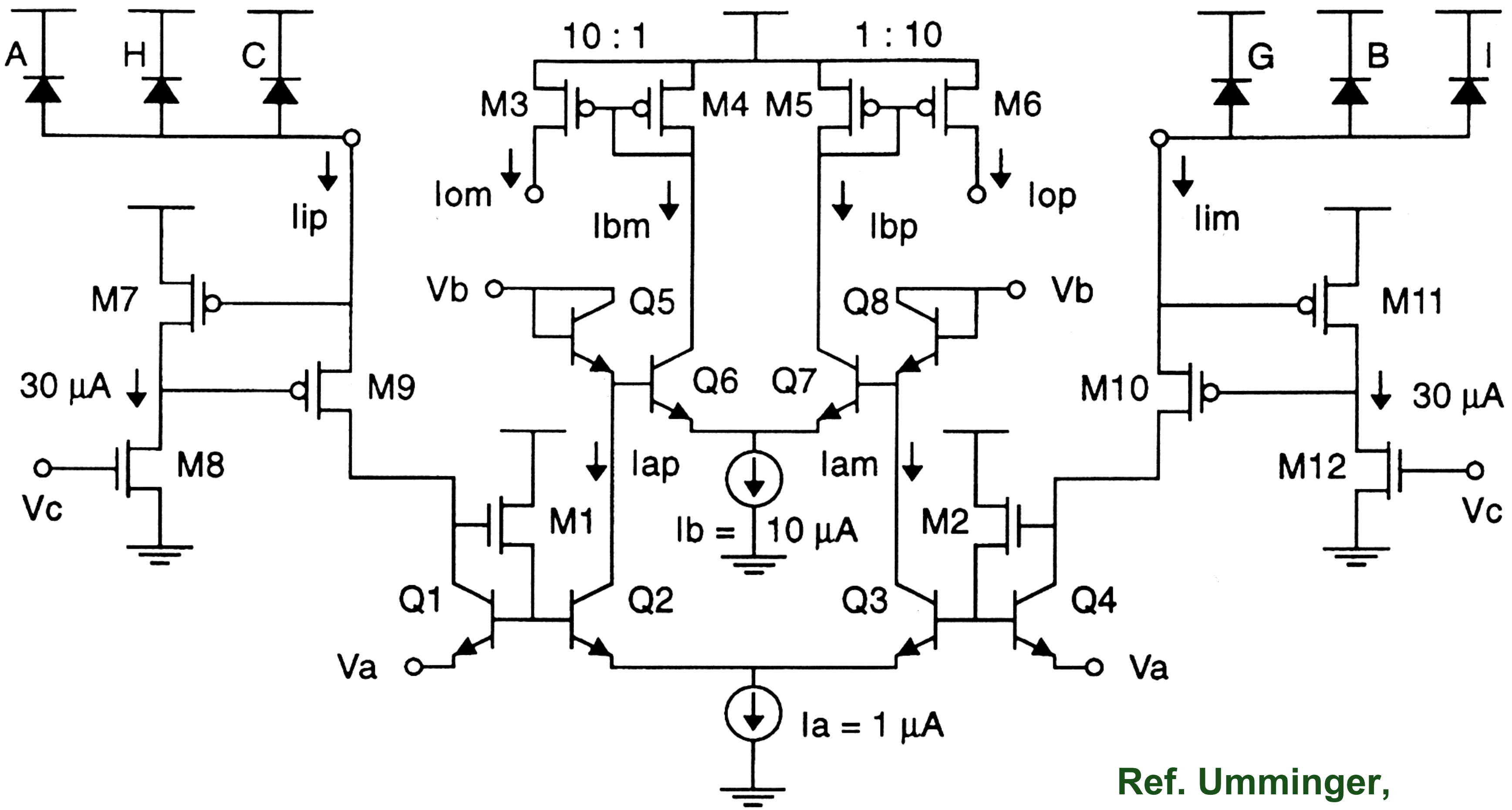
$$R_{OUTOL} = r_{o2}\,(1 + g_{m2} r_{o1})$$

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

$$R_{OUT} = R_{OUTOL}\, LG \approx \infty$$

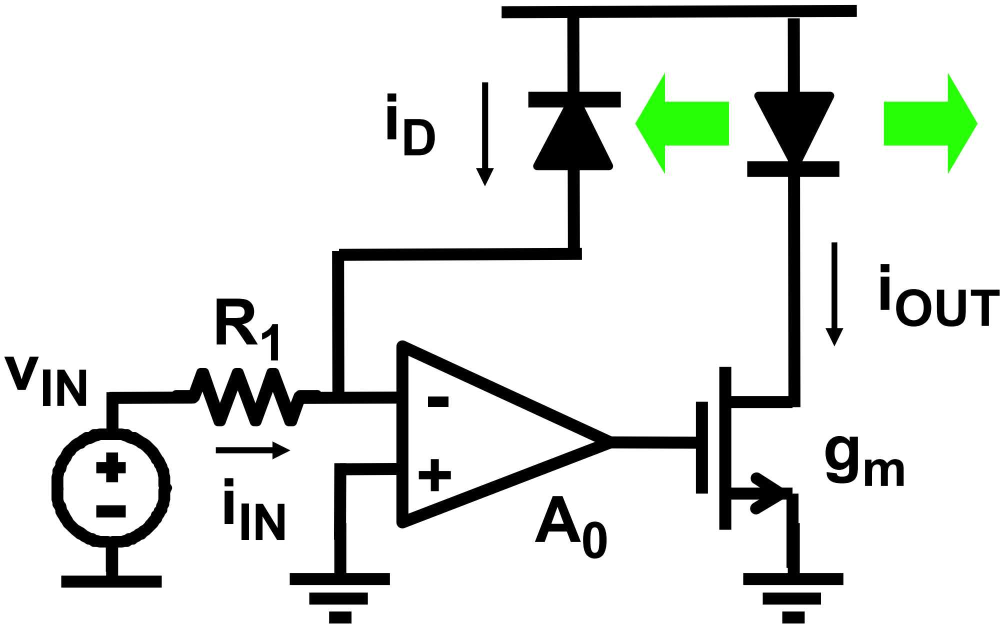
Hosticka, JSSC Dec.79, pp. 1111-1114; Sackinger, JSSC Febr.90, pp. 289-298;
Bult JSSC Dec.90, pp. 1379-1384

Differential current amplifier



Ref. Umminger,
JSSC Dec.95, 1382-1390

Linear laser diode driver



$$i_{OUT} = k\, i_{IN} = k\, \frac{v_{IN}}{R_1}$$

$$i_D = \frac{i_{OUT}}{k} \qquad LG = \frac{g_m A_0}{k}$$

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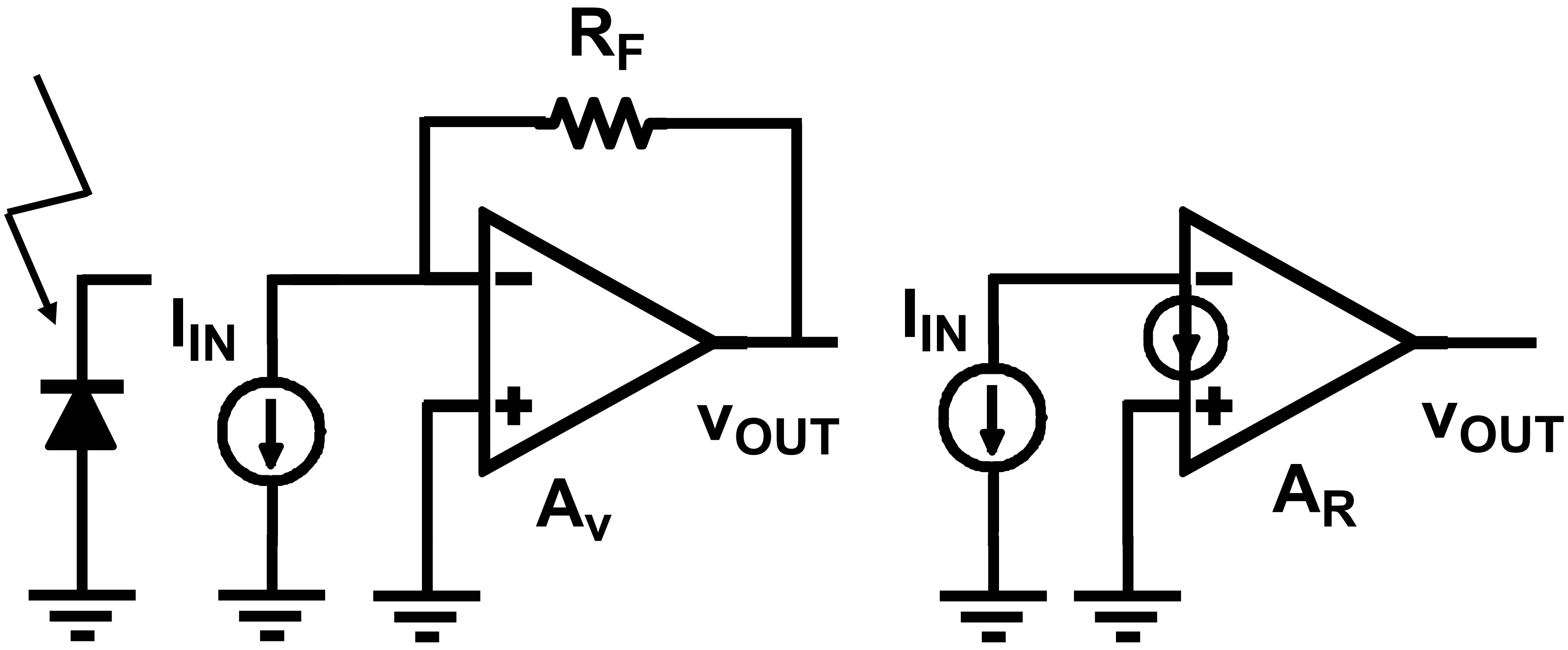
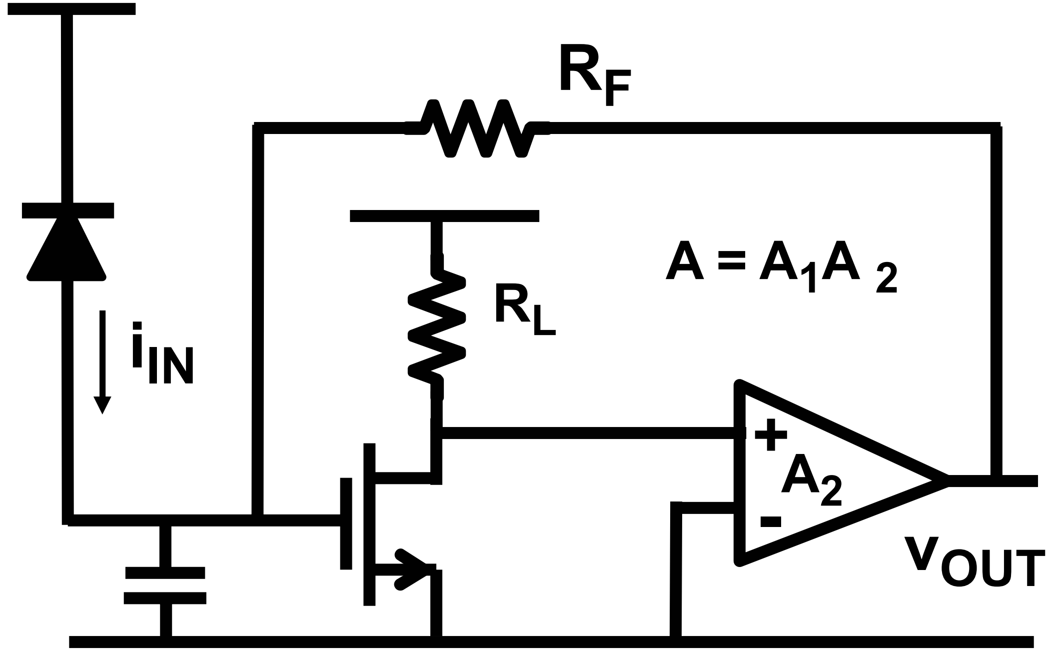
Optical receiver : Current or voltage amplifier



$$v_{OUT} = R_F I_{IN} \qquad v_{OUT} = A_R I_{IN}$$

Current detector with voltage amplifier



$C_P = C_D + C_{GS}$ $\quad A_1 = g_m R_L$

Noise matching : $C_D = C_{GS}$

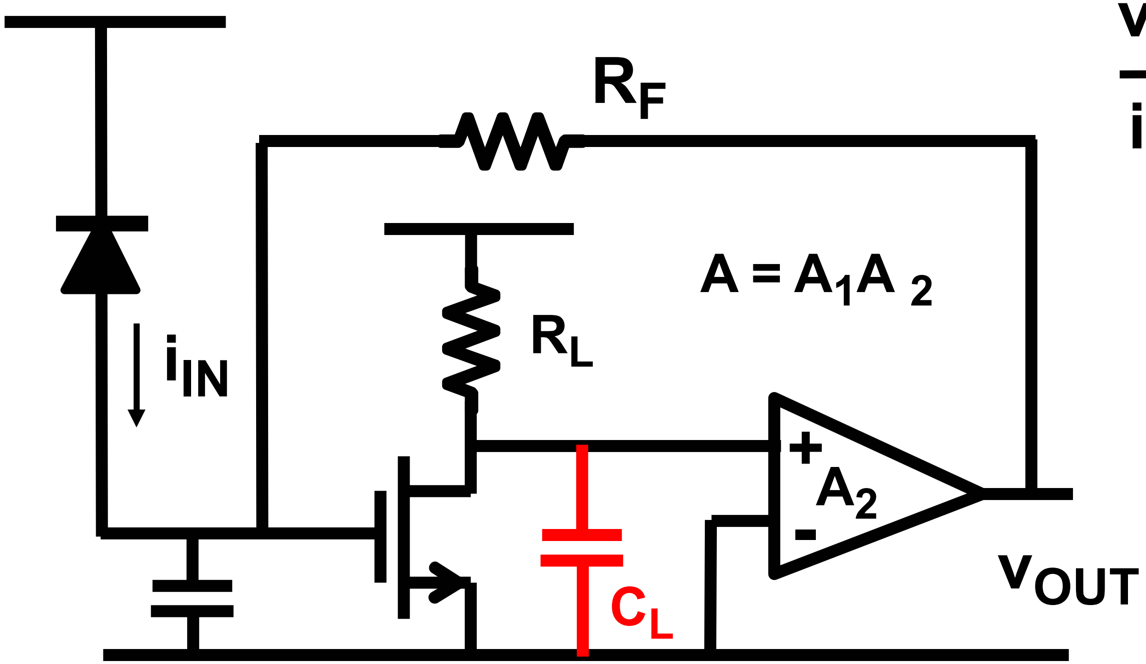
$$\frac{v_{IN}}{i_{IN}} = \frac{R_F}{A_1A_2} \frac{1}{1 + R_F \frac{C_P}{A_1A_2} s}$$

$$\frac{v_{OUT}}{i_{IN}} = R_F \frac{1}{1 + R_F \frac{C_P}{A_1A_2} s}$$

$$T = \frac{A_1A_2}{1 + R_F C_P s}$$

$$A_R \, BW \; (THz\Omega) = \frac{A_1A_2}{2\pi C_P}$$

Current detector with voltage amplifier



$C_P = C_D + C_{GS}$ $A_1 = g_m R_L$

No peaking if $R_L < \sqrt{\frac{R_F}{4 g_m A_2} \frac{C_P}{C_L}}$

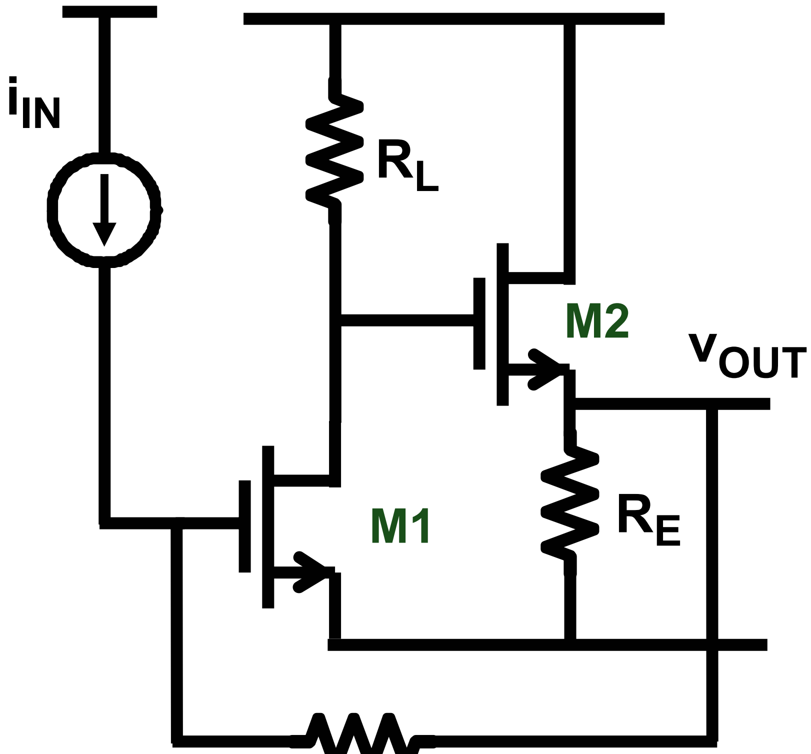
$$\frac{v_{IN}}{i_{IN}} = \frac{R_F}{A_1 A_2} \frac{1 + R_L C_L s}{1 + as + bs^2}$$

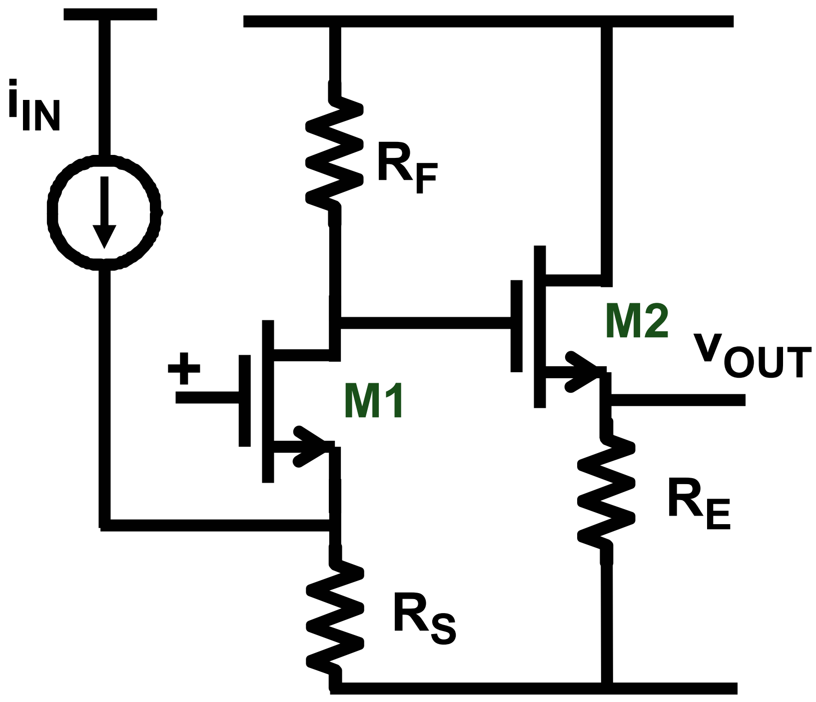
$$a = \frac{R_F C_P}{A_1 A_2}$$

$$b = \frac{R_F C_P R_L C_L}{A_1 A_2}$$

$$\frac{v_{OUT}}{i_{IN}} = R_F \frac{1}{1 + as + bs^2}$$

BW in voltage/current amplifier



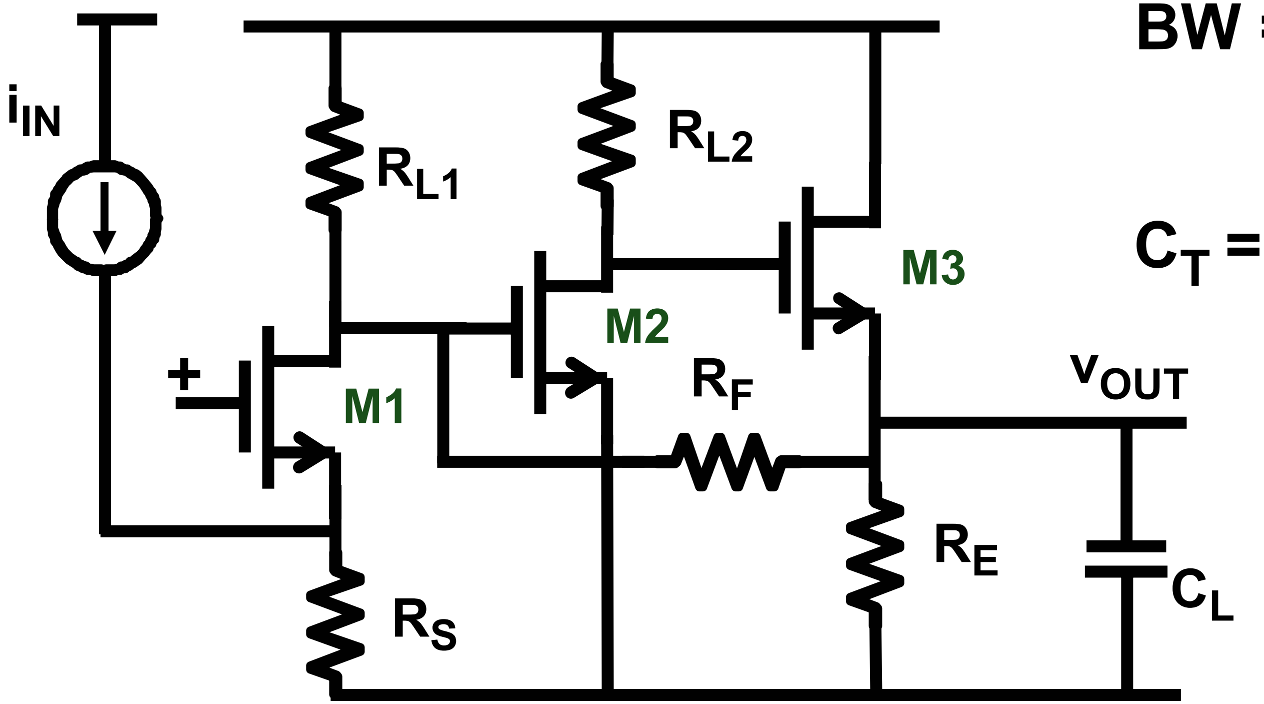


$R_S >> 1/g_{m1}$

$$BW = \frac{A_{v1}}{2\pi\ R_F(C_{GS1}+C_D)}$$

$$BW = \frac{1}{2\pi\ R_F(C_{GD2}+C_{DB1})}$$

Current detector with input cascode



$$BW = \frac{A_{v2}}{2\pi \; R_F//R_{L1}C_T}$$

$$C_T = C_{GS2} + A_{v2}C_{GD2}$$

$$A_{v2} = g_{m2}R_{L2}$$

$$v_{OUT} = R_F \; i_{IN}$$

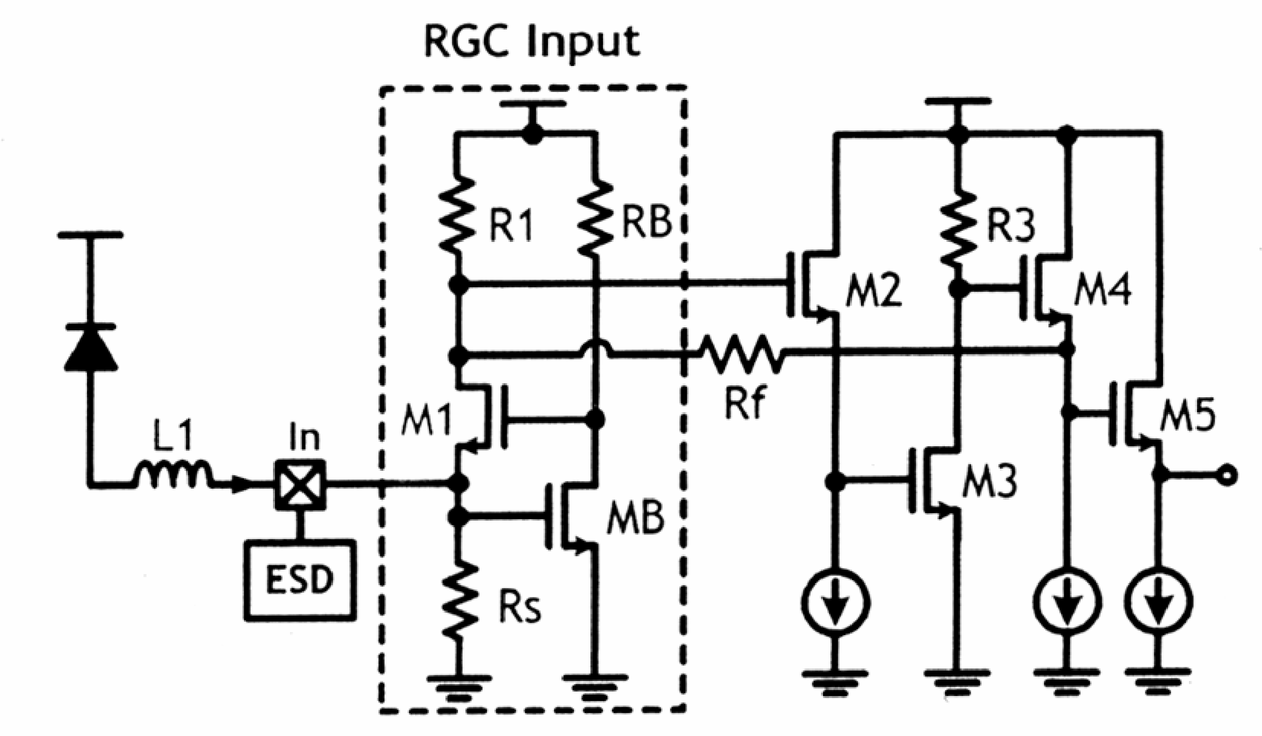
$$R_{OUT} = \frac{1/g_{m3}}{A_{v2}}$$

Z_{IN} independent of f !

$R_S >> 1/g_{m1}$

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

Current detector with regulated cascode



5 V 17 mA

$C_D = 0.5$ pF

$R_F = 800\ \Omega$

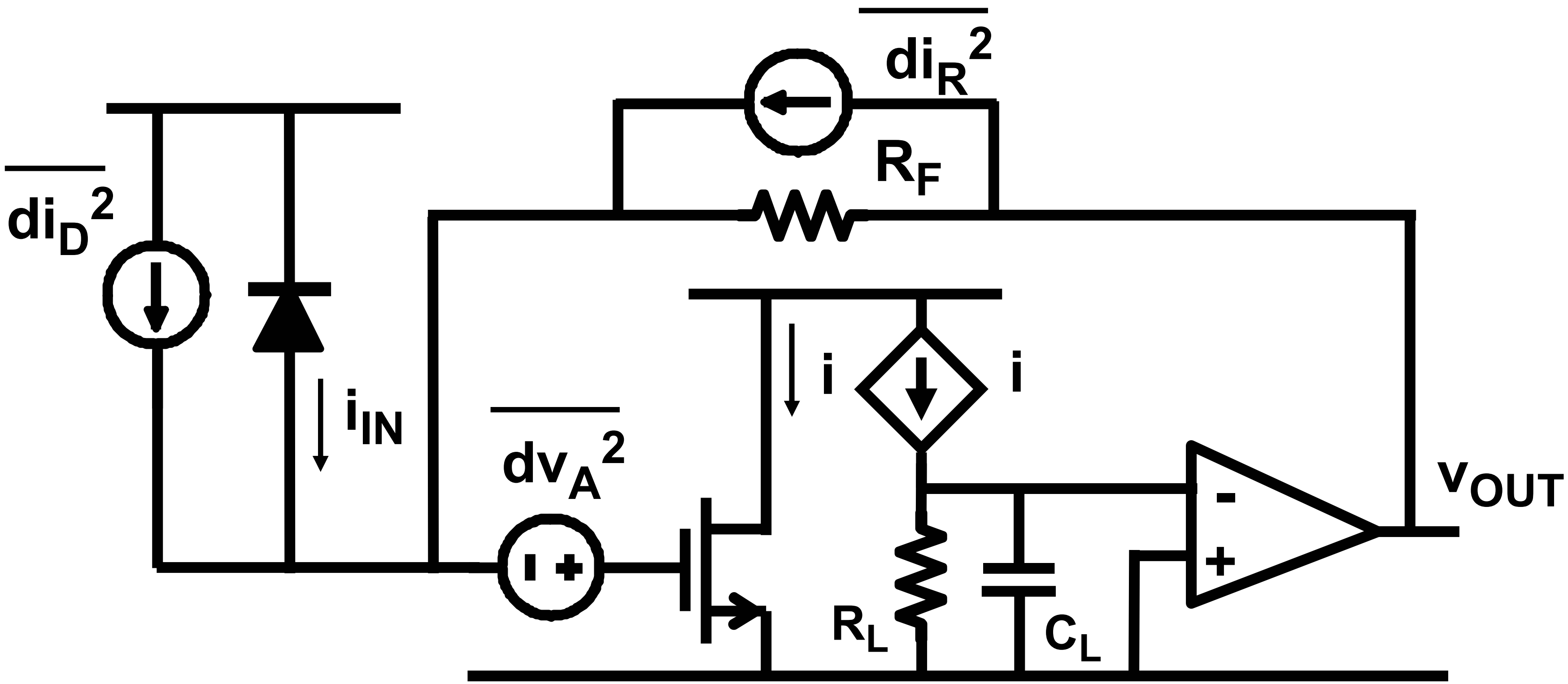
BW = 1 GHz

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

BW independent of C_D ! **Current noise : R_S & R_F // R_1**

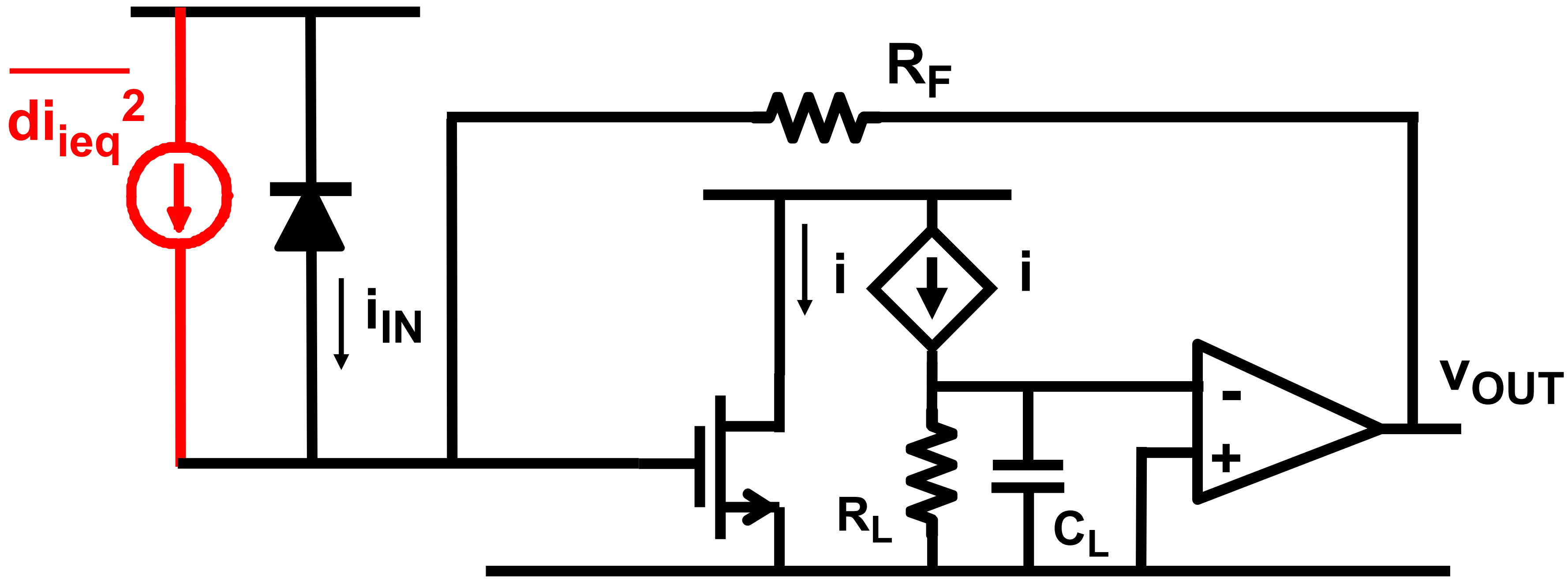
Park, JSSC Jan. 04, 112-120

Noise sources of detector voltage amplifier



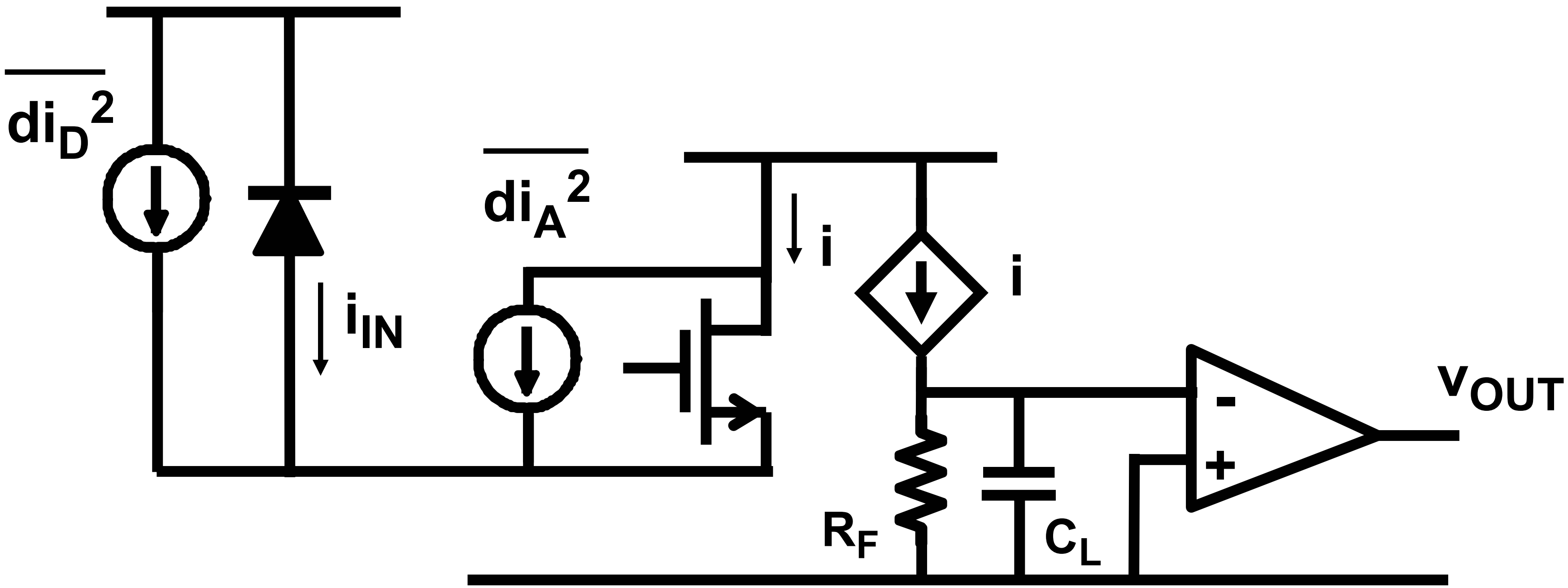
$\overline{di_D^2} = 2qI_D\ df$ $\quad \overline{di_R^2} = \frac{4kT}{R_F}\ df$ $\quad \overline{dv_A^2} = 4kT\ (\frac{2/3}{g_m})\ df$

Noise density of detector voltage amplifier



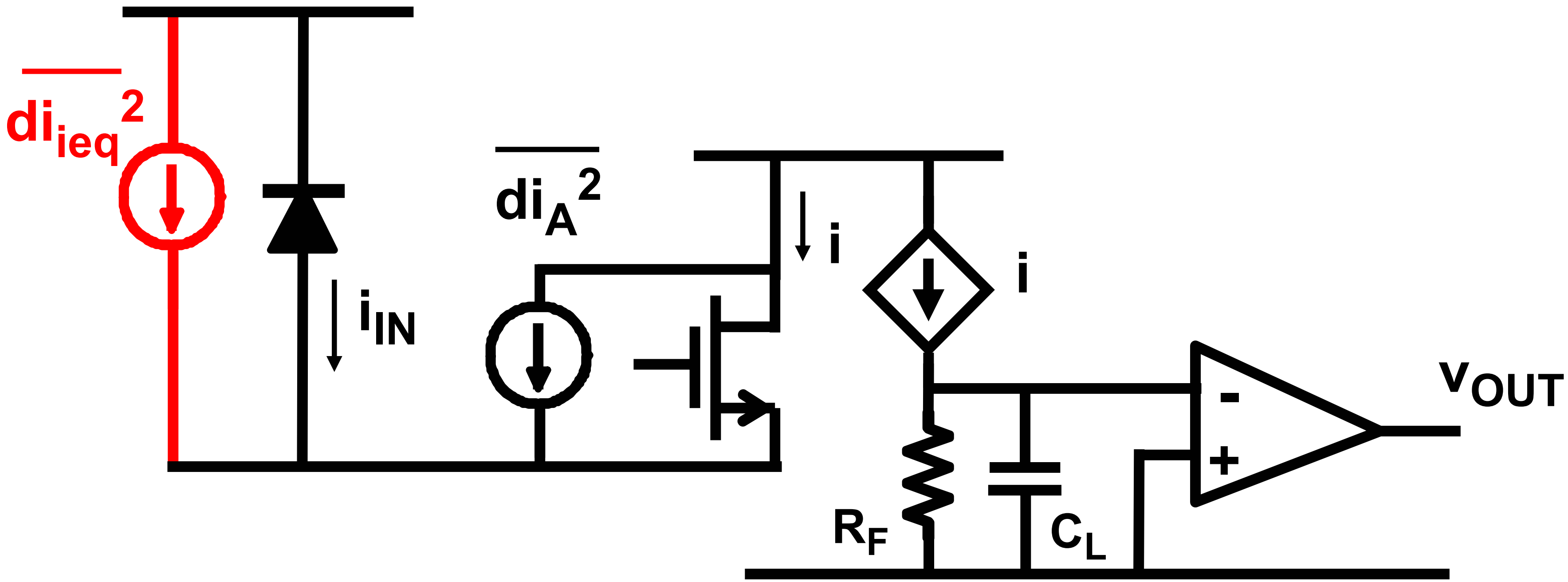
$$\overline{di_{ieq}^2} = \overline{di_D^2} + \overline{di_R^2} + \frac{\overline{dv_A^2}}{R_F^2} \approx \overline{di_D^2} + \overline{di_R^2} \quad \text{if } R_F > \frac{2/3}{g_m}$$

Noise sources of detector current amplifier



$$\overline{di_D^2} = 2q\, I_D\, df \qquad \overline{di_A^2} = 4kT\, \frac{2}{3}\, g_m\, df$$

Noise density of detector current amplifier



$$\overline{di_{ieq}^2} = \overline{di_D^2} + 4kT\,\frac{2}{3}\,g_m\,df$$ **is transistor noise !**

Comparison of noise densities

Voltage amp.: $\overline{i_{IN}^2} = \overline{di_R^2} = \frac{4kT}{R_F}\,df$

Current amp.: $\overline{i_{IN}^2} = \overline{di_A^2} = 4kT\,\frac{2}{3}\,g_m\,df$

➡ **Voltage amplifier better when $R_F > \frac{3}{2}\,\frac{1}{g_m}$**

Comparison of integrated noise

Large I_D : $\overline{i_{IN}^2} = \overline{di_D^2}\,(BW\,\frac{\pi}{2})$

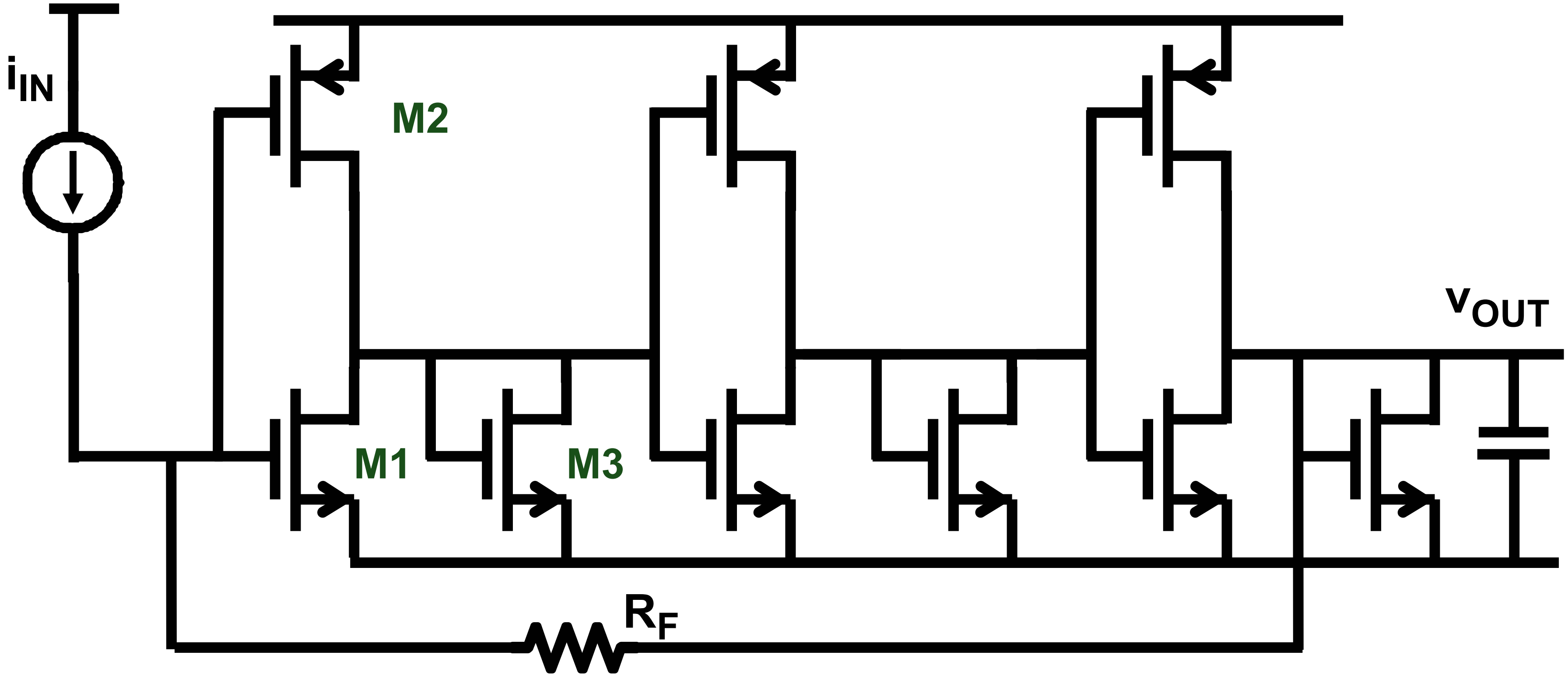
Small I_D :

Voltage amp.: $\overline{i_{IN}^2} = \overline{di_R^2}\,(BW\,\frac{\pi}{2}) = \frac{kT}{R_L}\left(\frac{R_L}{R_F}\right)^2 \frac{g_m}{C_P}$

Current amp.: $\overline{i_{IN}^2} = \overline{di_A^2}\,(BW\,\frac{\pi}{2}) = \frac{2}{3}\,\frac{kT}{R_F}\,\frac{g_m}{C_L}$

➡ **Voltage amplifier better when $R_F > \frac{3}{4} R_L$**

CMOS photodiode amplifier

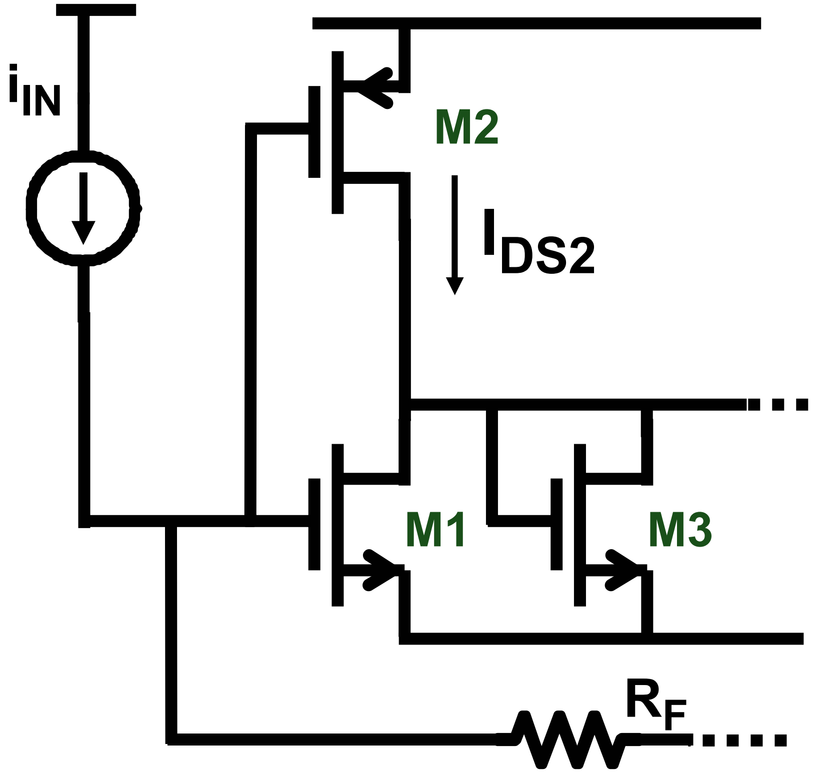


150 kΩ x 120 MHz = 18 THzΩ   0.5 pA/√Hz

450 MHz per cell

Ref.Ingels, JSSC Dec 1994, 1552-1559

CMOS wideband amplifier cell



M_1 & M_3 : same V_{GS} & V_{DS}

$K'_n \approx 2K'_p$

All L are L_{min}

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

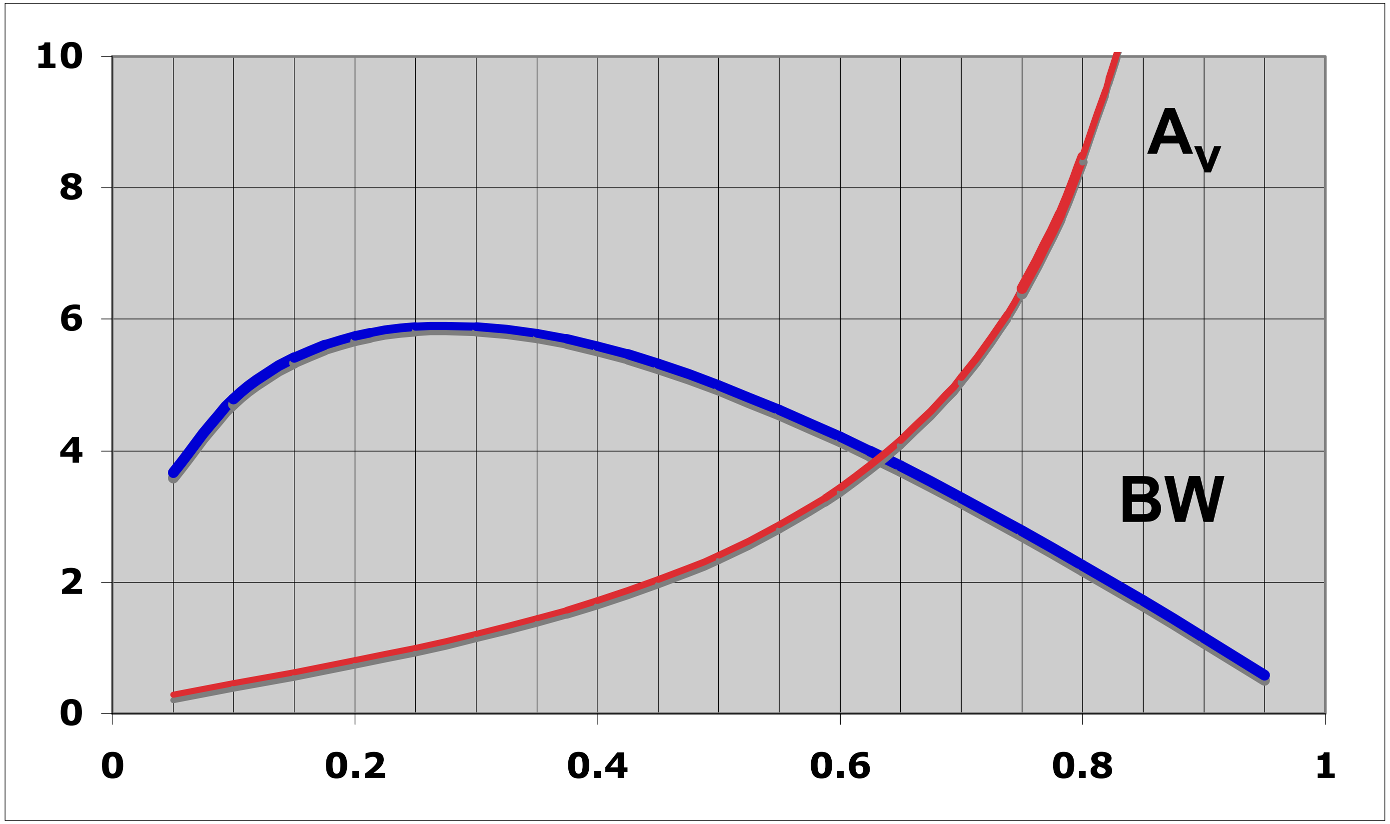
$$g_m = 2\sqrt{K'_n I_{DS} W/L}$$

$I_{DS1} = \lambda I_{DS2}$

$I_{DS3} = (1 - \lambda) I_{DS2}$

$V_{GS1} = V_{GS3}$: $W_3 = W_1 \dfrac{1 - \lambda}{\lambda}$

CMOS wideband amplifier : gain and bandwidth



λ

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

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

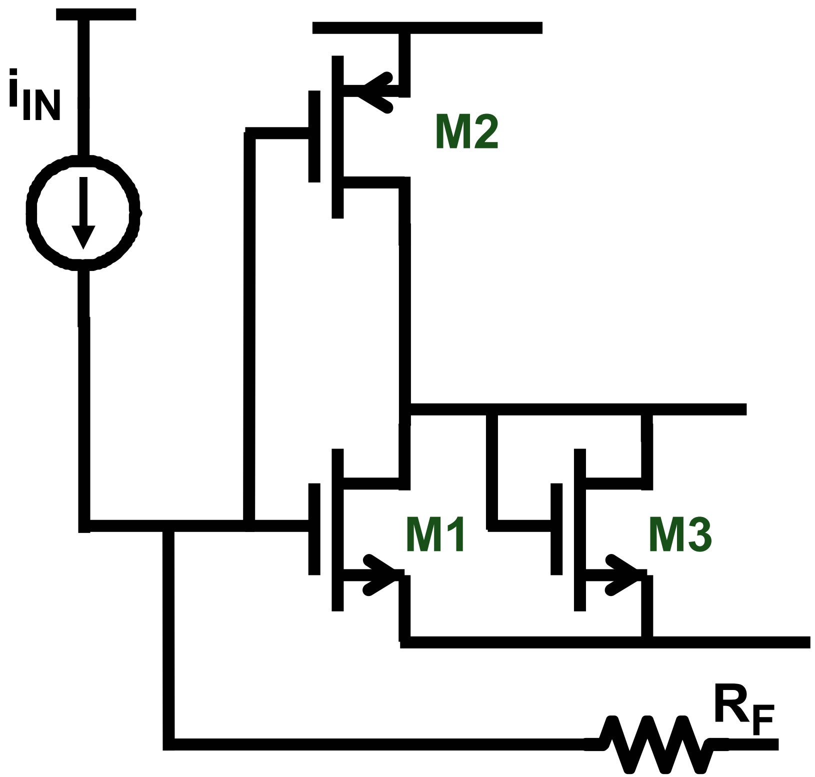
$$\sim \frac{(1-\lambda)\sqrt{\lambda W_1}}{W_1(2-\lambda)+\lambda W_2}$$

$W_1 = 2$
$W_2 = 4$

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

$C_{DB} \approx C_{GS} \approx kW \qquad k \approx 2\ fF/\mu m$

Integrated resistor



R_F ? Poly R : large size : large L
distributed C :
45° phase shift at 100 MHz

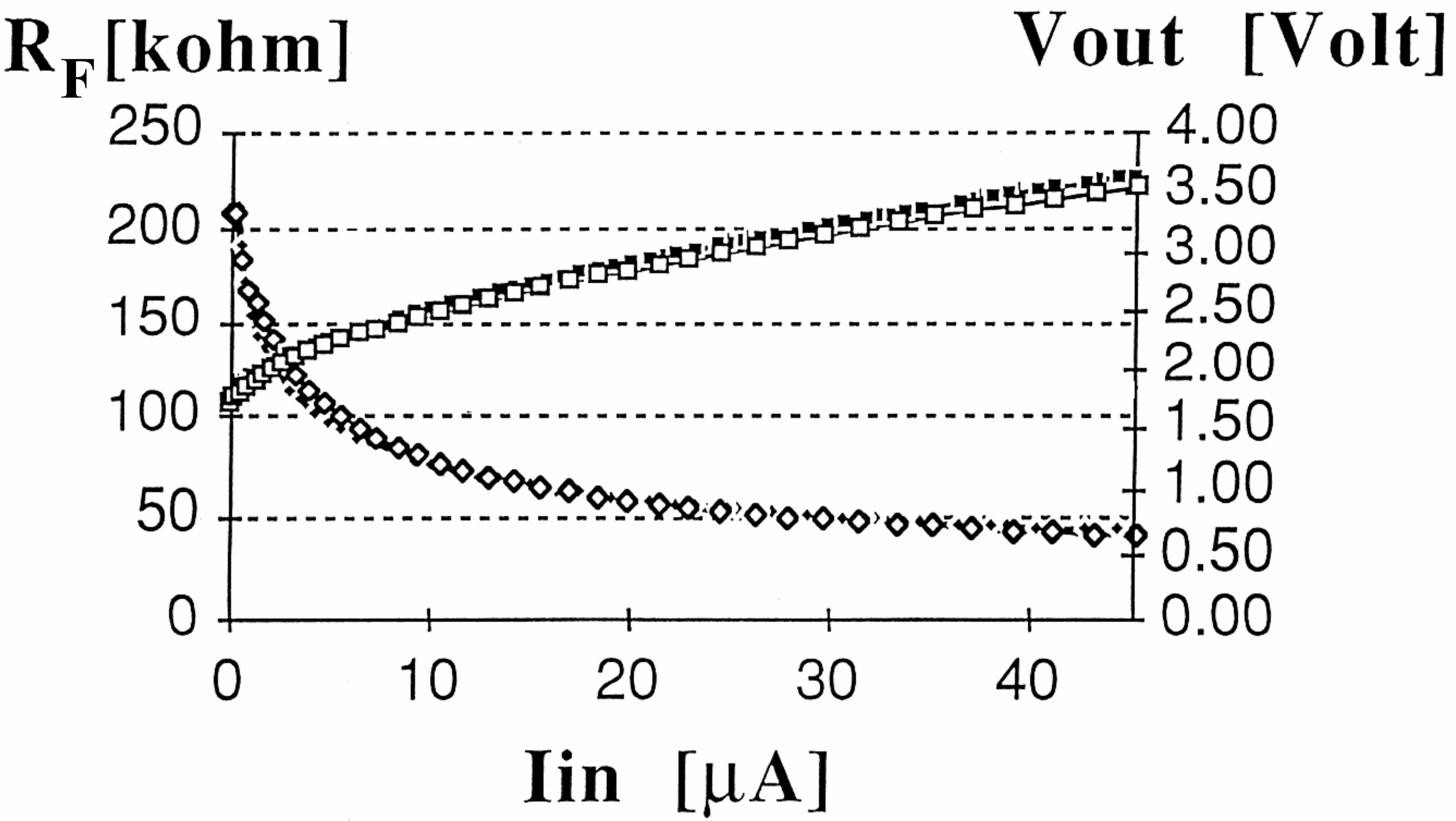
$$f_{-3dB} = \frac{1}{2\pi} \frac{2.43}{R_S C_0 L^2}$$

R_S = sheet res. (Ω / □)
C_0 = unit cap. (F/cm^2)

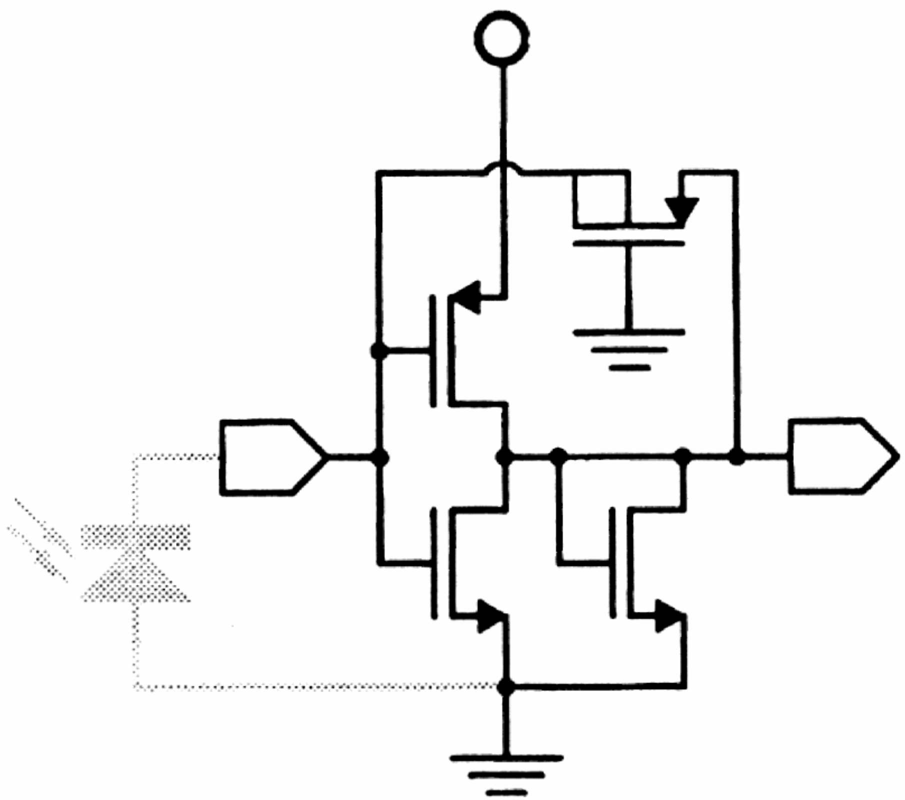
MOST : W = 1.3 μm & L = 1 μm
allows dynamic compression

Glaser; IC Engineering
Add.Wesley, p.132

Gain compression



1 Gb/s 1 kΩ transimpedance stage



pMost vs nMOST :

nMOST R increases for
larger diode currents !
pMOST gives compression !

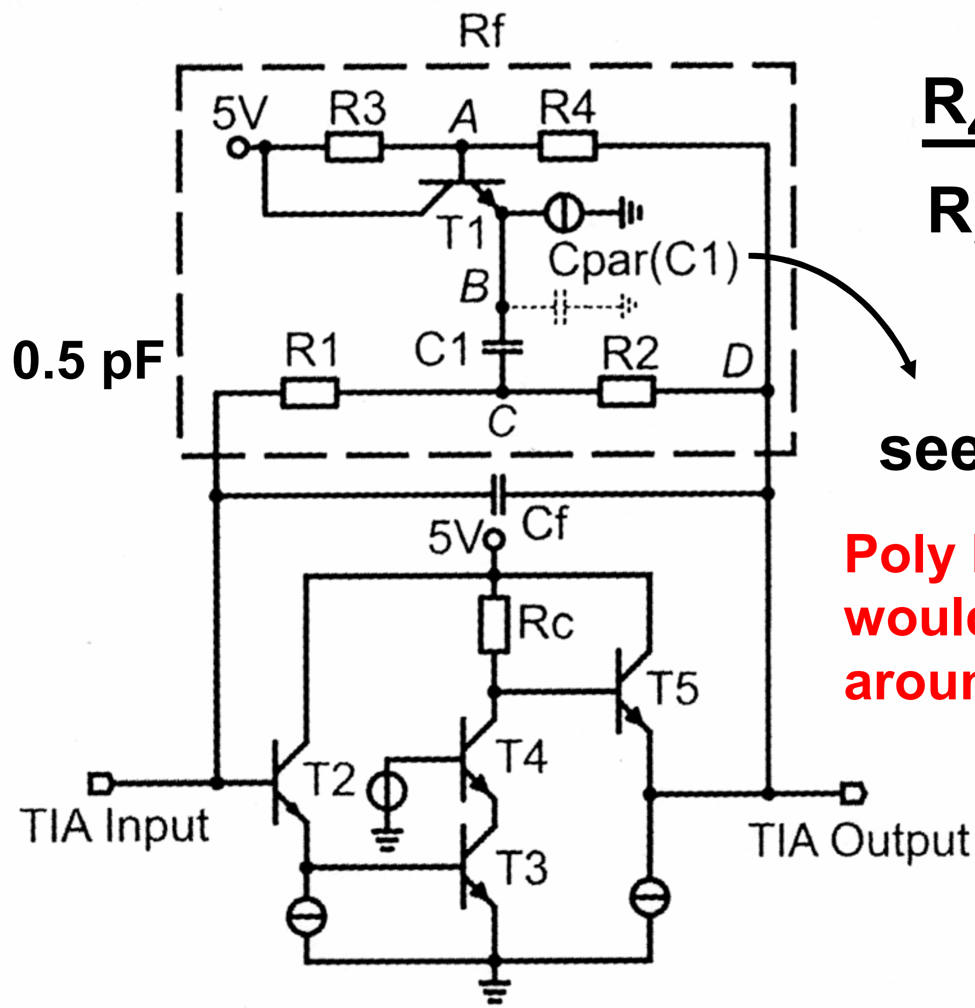
C_d = 0.8 pF ≈ C_{GS}

Capacitive noise matching !

BW = 500 MHz
5 mA (5V)
0.7 μm CMOS

Ref.Ingels, JSSC July 1999, 971-977

High-frequency Resistance RF



$$\frac{R_4}{R_3} = \frac{R_2}{R_1} = 2$$

$R_1 + R_2 = 200\ k\Omega$

$R_3 + R_4 = 4\ k\Omega$

sees $1/g_{m1}$

Poly $R_F = 200\ k\Omega$ would cut off around 67 MHz !

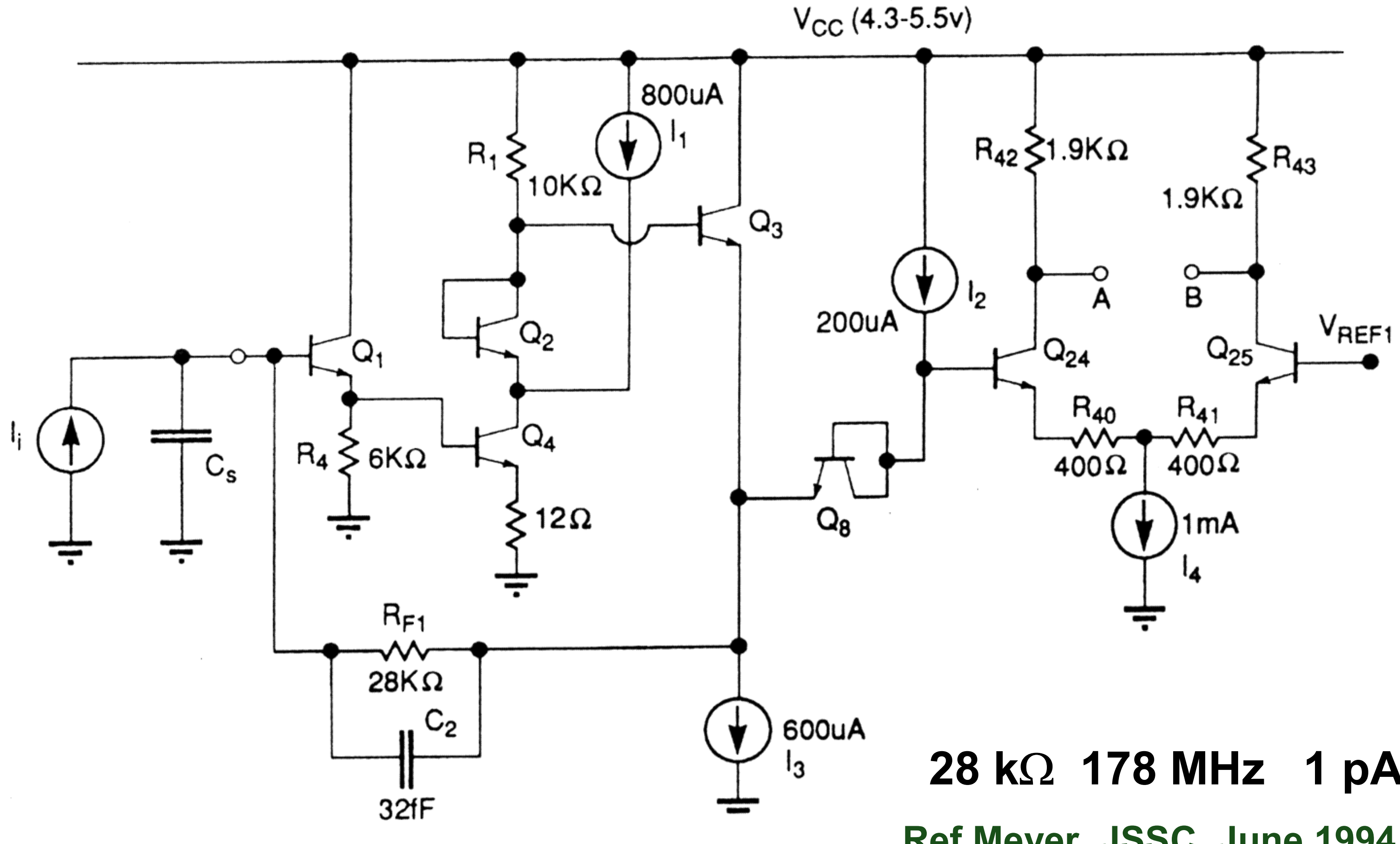
$C_d = 0.1\ pF$

180 kΩ 380 MHz
68 THzΩ

14 mA (5 V)
0.6 μm BiCMOS

Seidl, ISSCC 04, 470-471

BICMOS transimpedance amplifier

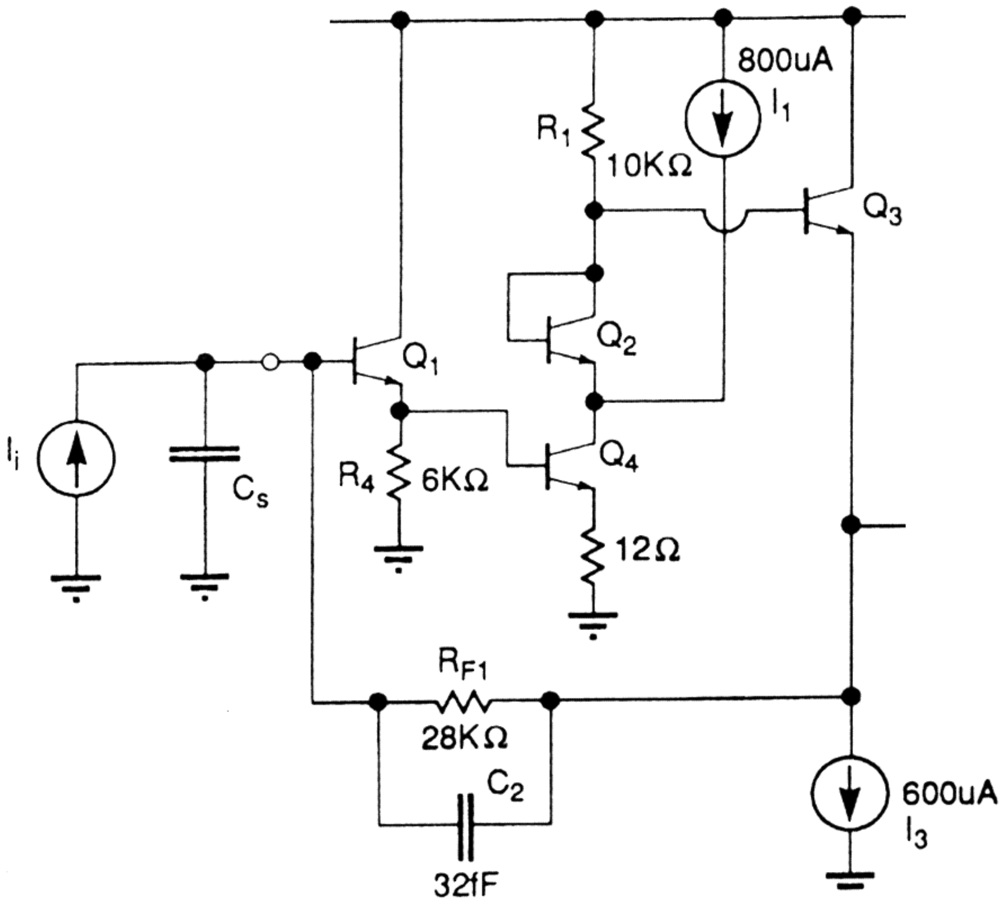


28 kΩ 178 MHz 1 pA/√Hz

Ref.Meyer, JSSC June 1994, 701-706

178 MHz

BICMOS transimpedance amplifier



178 MHz

$$A_v = \frac{R_1 \,//\, ..}{12 + 1/g_{m4}} = \frac{5\ k\Omega}{12 + 28} = 125$$

$$R_i = \frac{R_{F1}}{1 + A_v} = 240\ \Omega$$

$$C_i = (1 + A_v)\, C_2 = 4\ pF$$

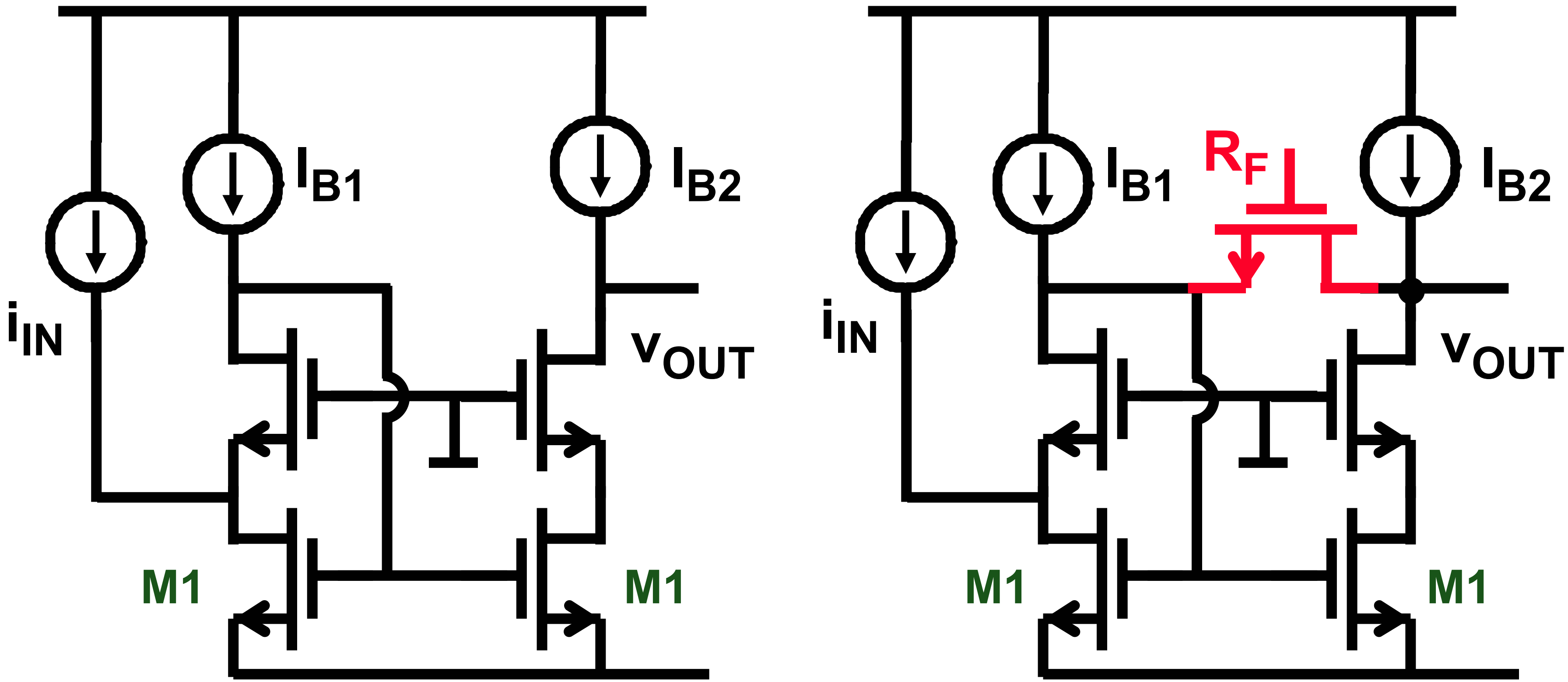
$$\overline{di_i^2} = 2qI_{B1}df + \frac{4kT}{R_{F1}} df$$

$$= (0.4 + 0.6)10^{-24} \approx 10^{-24}\ A^2/Hz$$

28 kΩ   178 MHz   1 $pA_{RMS}/\sqrt{Hz}$

Ref.Meyer, JSSC June 1994, 701-706

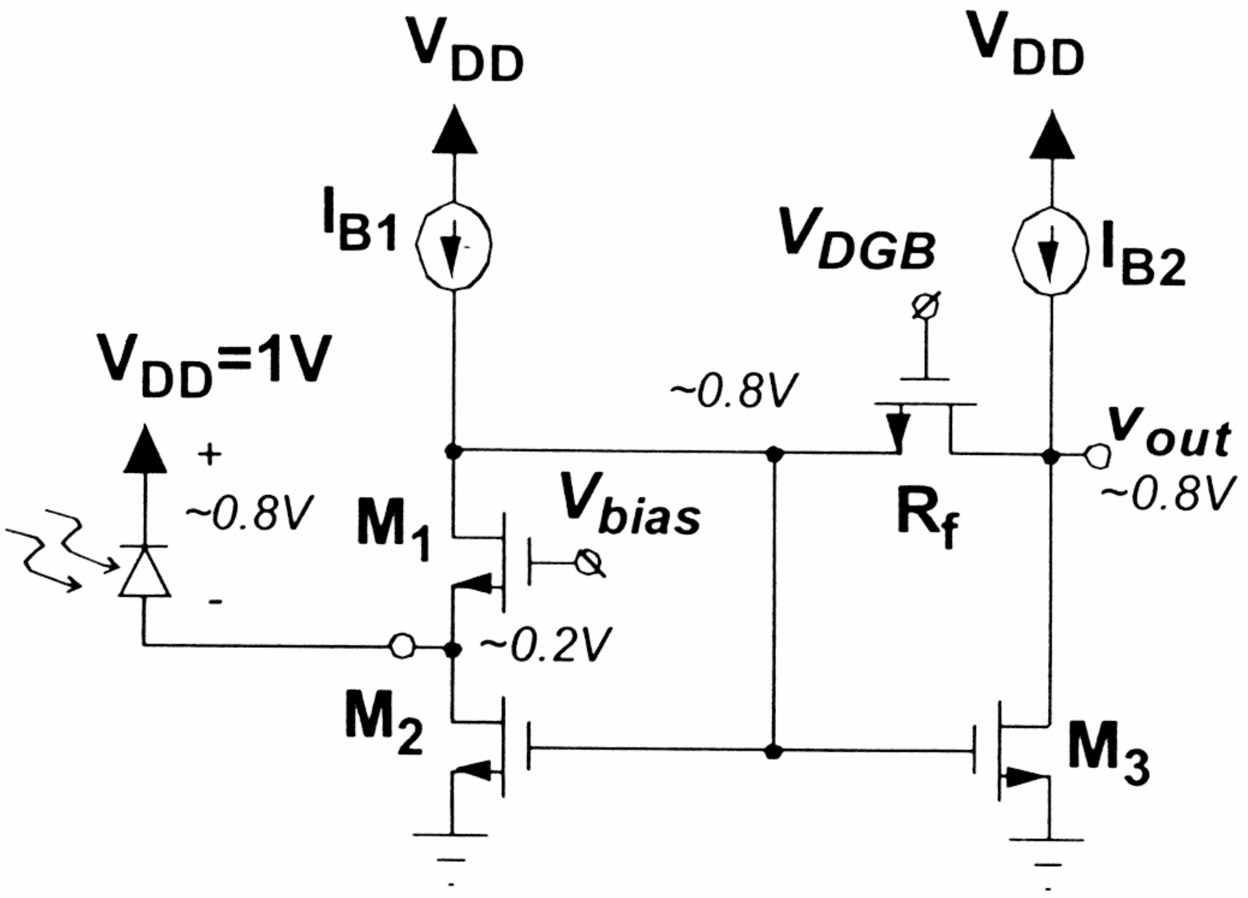
Low-voltage transimpedance amplifier



If $R_F > 1/g_{m1}$: $v_{OUT} = - R_F \, i_{IN}$

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

75 Mb/s optical receiver in CMOS



C_d = 1 pF

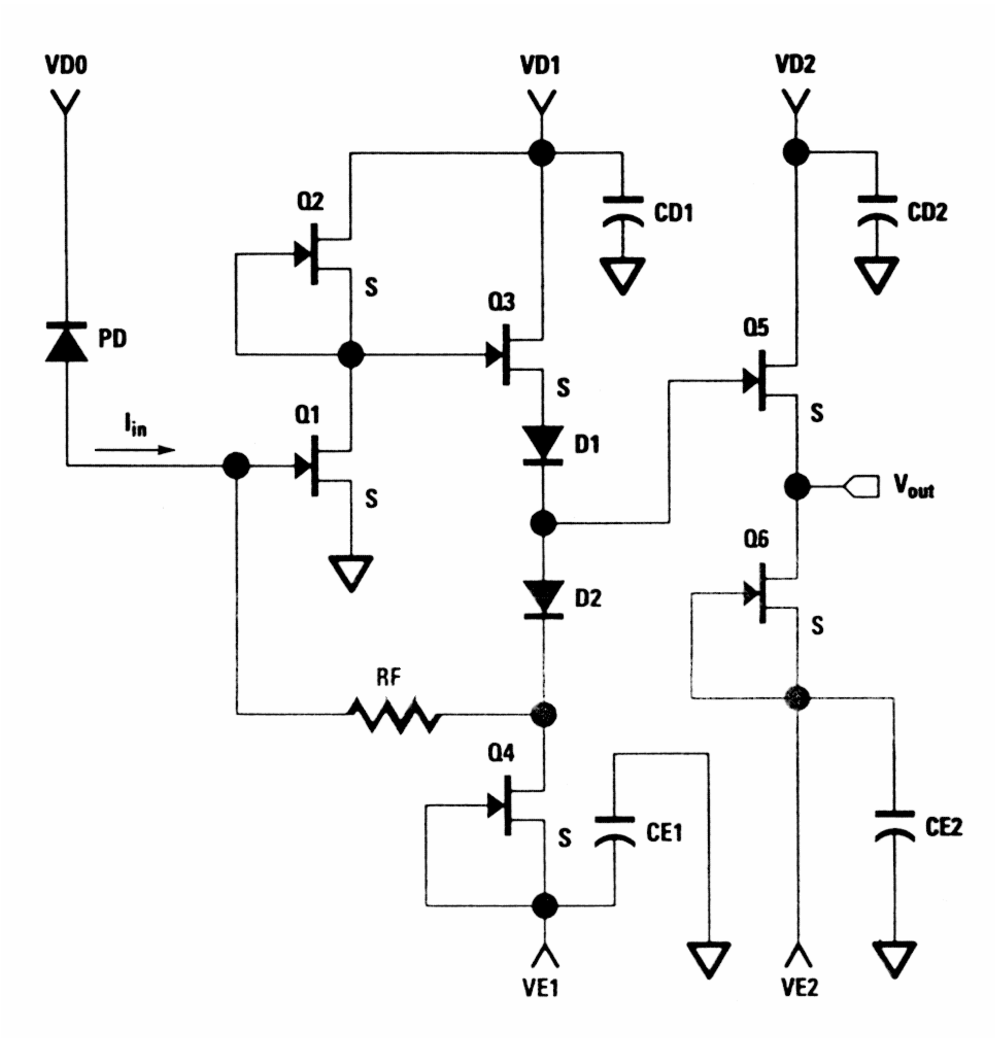
(40 μA)
2.4 kΩ
45 MHz

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

0.35 μm CMOS
1 V (1 mA)

Ref. Phang, ISSCC 2001 218-219

GaAs 10 Gb/s receiver



HP - GaAs MODIC :
depletion nMOST's

560 V/W

flip-chip PD :
- -3 dB at 7.2 GHz
- 10 pA/√Hz

wire bond :
- -3 dB at 4.2 GHz
- 20 pA/√Hz

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- Transimpedance amplifiers for
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