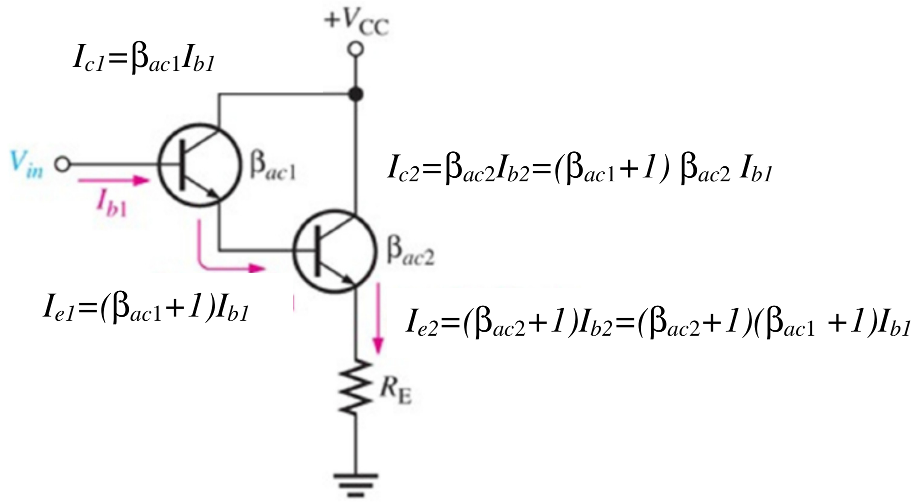
Esempi semplici di circuiti multi-stadio

1) Darlington

Stadio a 2 BJT: $CC + CC$



$$I_{tot} = I_{c1} + I_{c2} = \left(\beta_1 + \beta_2\left(\beta_1 + 1\right)\right) I_{b1} = \left(\beta_1\beta_2 + \beta_1 + \beta_2\right) I_{b1}$$

$$\beta = \beta_1\beta_2 + \beta_1 + \beta_2$$

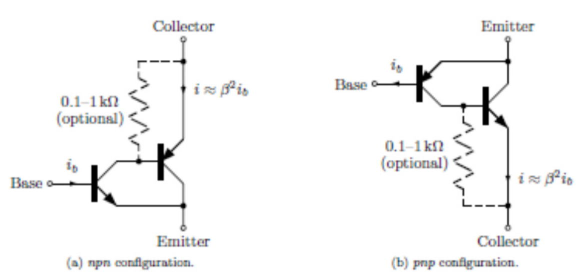
$$\beta_i \gg 1 \rightarrow \beta_1\beta_2 \gg \beta_1 + \beta_2 \rightarrow \beta \approx \beta_1\beta_2 \sim 10^4\,!$$

$$\rightarrow R_{in} \sim \beta_1\beta_2 R_E$$

Svantaggio principale:

$V_{BE} \sim 1.3\ V$ per zona attiva ($\rightarrow$ 2 diodi)

Versione a 'Sziklai Pair': $V_{BE} \sim 0.65\ V$ per zona attiva ($\rightarrow$1 diodo)



$$i = i_{E1} + i_{C2}$$

$$i_{E1} = \left(\beta_1 + 1\right) i_{B1}, i_{C2} = \beta_2 i_{B2}$$

$$i_{B2} = i_{C1} = \beta_1 i_{B1} \rightarrow i_{C2} = \beta_2\beta_1 i_{B1}$$

$\rightarrow i = i_{E1} + i_{C2} = \left(\beta_1 + 1\right) i_{B1} + \beta_2\beta_1 i_{B1} = \left(\beta_1 + 1 + \beta_2\beta_1\right) i_{B1}$ corr. emettitore

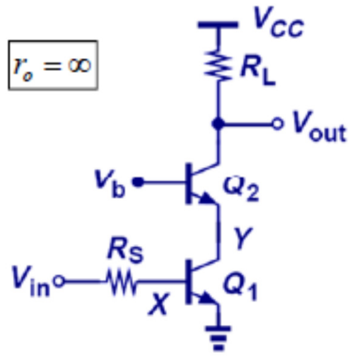
$\rightarrow$ Corr. di 'collettore' = $\left(\beta_1 + \beta_2\beta_1\right) i_{B1} \approx \beta_2\beta_1 i_B$

2) Cascode

Stadio a 2 BJT: *CE + CB*

Alta impedenza di ingresso (CE)

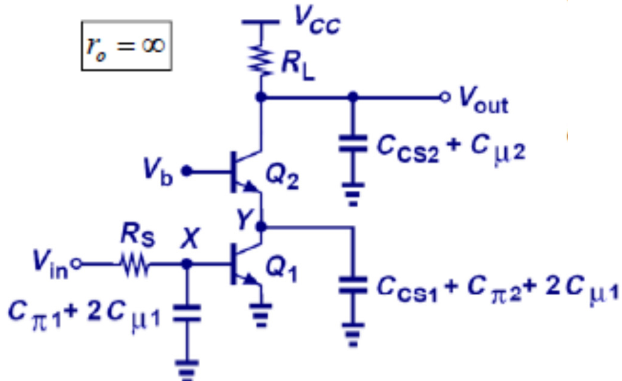
Banda larga (CB) - Riduzione drastica di effetto Miller



$$A_{v,XY} \equiv \frac{v_X}{v_Y} = -g_{m1}\left(\frac{1}{g_{m2}}\right) \approx -1$$

$$\Rightarrow \quad C_X \approx 2C_{XY}$$

Identificazione capacita':



Frequenze di taglio:

$$\omega_{p,X} = \frac{1}{(R_S \| r_{\pi 1})(C_{\pi 1} + 2C_{\mu 1})}$$

$$\omega_{p,Y} = \frac{1}{\frac{1}{g_{m2}}(C_{CS1} + C_{\pi 2} + 2C_{\mu 1})}$$

Inoltre:

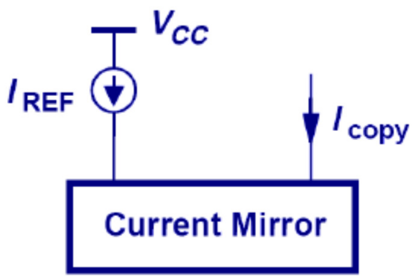
$$\omega_{p,out} = \frac{1}{R_L\left(C_{CS2} + C_{\mu 2}\right)}$$

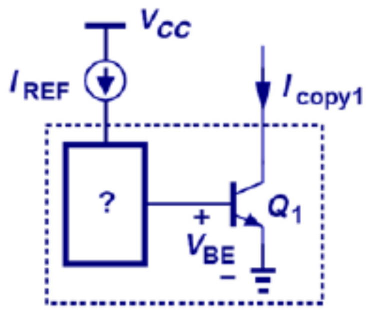
Quindi:

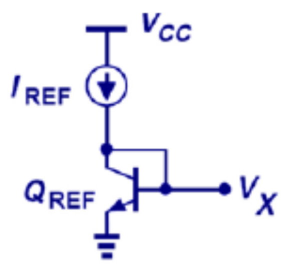
$$Z_{in} = r_{\pi 1} \,||\, \frac{1}{j\omega\left(C_{\pi 1} + 2C_{\mu 1}\right)}$$

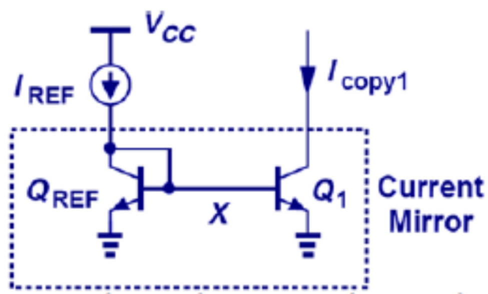
$$Z_{out} = R_L \,||\, \frac{1}{j\omega\left(C_{\mu 2} + C_{CS2}\right)}$$

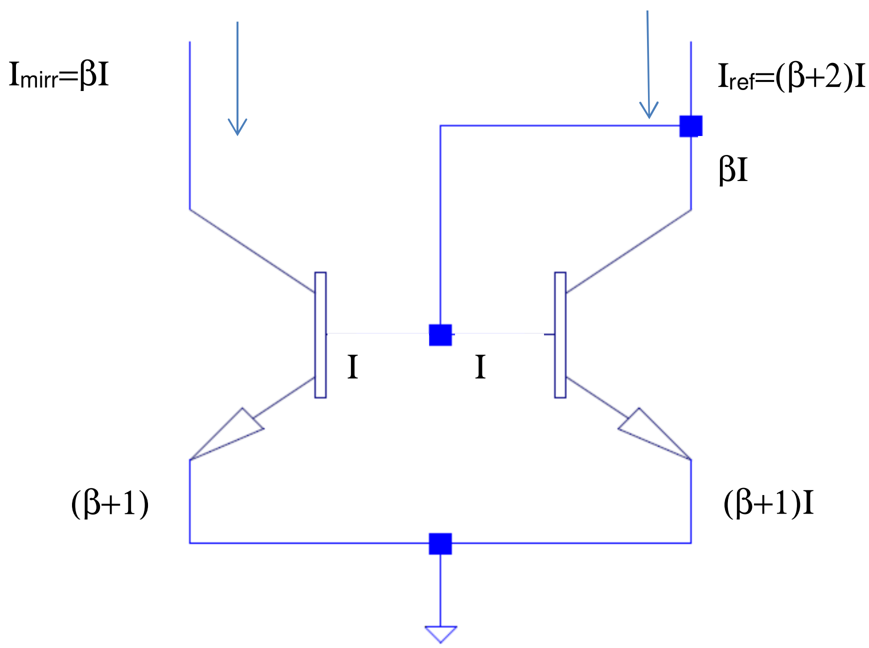
3) Current mirror











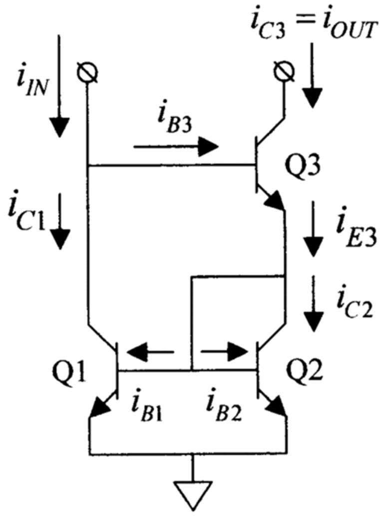
$$I_{ref} = I_{C1} + 2I, I_{C1} = \beta I \rightarrow I_{ref} = (\beta + 2) I$$

$$I_{mirr} = I_{C2} = \beta I$$

Matching fra correnti:

$$\frac{I_{mirr}}{I_{ref}} = \frac{\beta}{\beta + 2} \sim \text{OK } @ 1 - 2\%$$

Current mirror di Wilson:



Assumendo i 3 BJT identici:

$$i_{B1} = i_{B2} \equiv I$$

$$\rightarrow i_{C1} = i_{C2} = \beta I$$

$$i_{IN} = i_{C1} + i_{B3} = \beta I + \frac{1}{\beta+1} i_{E3}$$

$$i_{E3} = i_{C2} + 2I = (\beta+2)I$$

$$\rightarrow i_{IN} = i_{C1} + i_{B3} = \beta I + \frac{\beta+2}{\beta+1} I = \left(\beta + \frac{\beta+2}{\beta+1}\right) I$$

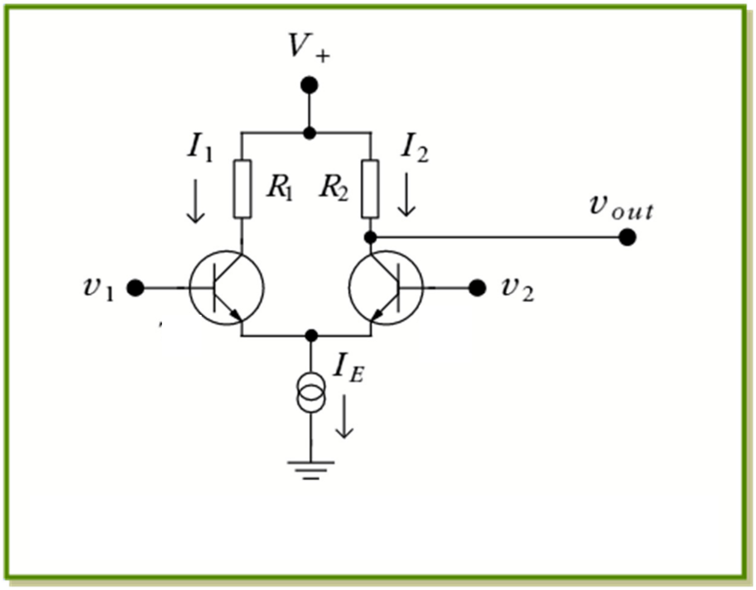
$$i_{IN} = \frac{\beta(\beta+1)+\beta+2}{\beta+1} I = \frac{\beta^2+2\beta+2}{\beta+1} I$$

$$i_{C3} = \frac{\beta}{\beta+1} i_{E3} = \frac{\beta(\beta+2)}{\beta+1} I$$

$$\rightarrow \frac{i_{C3}}{i_{IN}} = \frac{\beta(\beta+2)}{\beta+1} \frac{\beta+1}{\beta^2+2\beta+2} = \frac{\beta(\beta+2)}{\beta^2+2\beta+2} \simeq 1$$

Matching entro $\sim 10^{-4}$

4) Amplificatore differenziale



$$v_1 = v_{B1}, v_2 = v_{B2}$$
$$I = i_{E1} + i_{E2}$$
$$I_1 = i_{C1}, I_2 = i_{C2}$$
$$R_{C1} = R_{1,} R_{C2} = R_2$$

$$i_{E1} = \frac{I_S}{\alpha} \exp\left[\left(v_{B1} - v_E\right)/V_T\right]$$
$$i_{E2} = \frac{I_S}{\alpha} \exp\left[\left(v_{B2} - v_E\right)/V_T\right]$$

$$\frac{i_{E1}}{i_{E2}} = \exp\left[\left(v_{B1} - v_{B2}\right)/V_T\right]$$

$$\frac{i_{E1}}{i_{E1} + i_{E2}} = \frac{i_{E1}}{I} = \frac{1}{1 + i_{E2}/i_{E1}} = \frac{1}{1 + \exp\left[\left(v_{B2} - v_{B1}\right)/V_T\right]}$$
$$\frac{i_{E2}}{i_{E1} + i_{E2}} = \frac{i_{E2}}{I} = \frac{1}{1 + i_{E1}/i_{E2}} = \frac{1}{1 + \exp\left[\left(v_{B1} - v_{B2}\right)/V_T\right]}$$

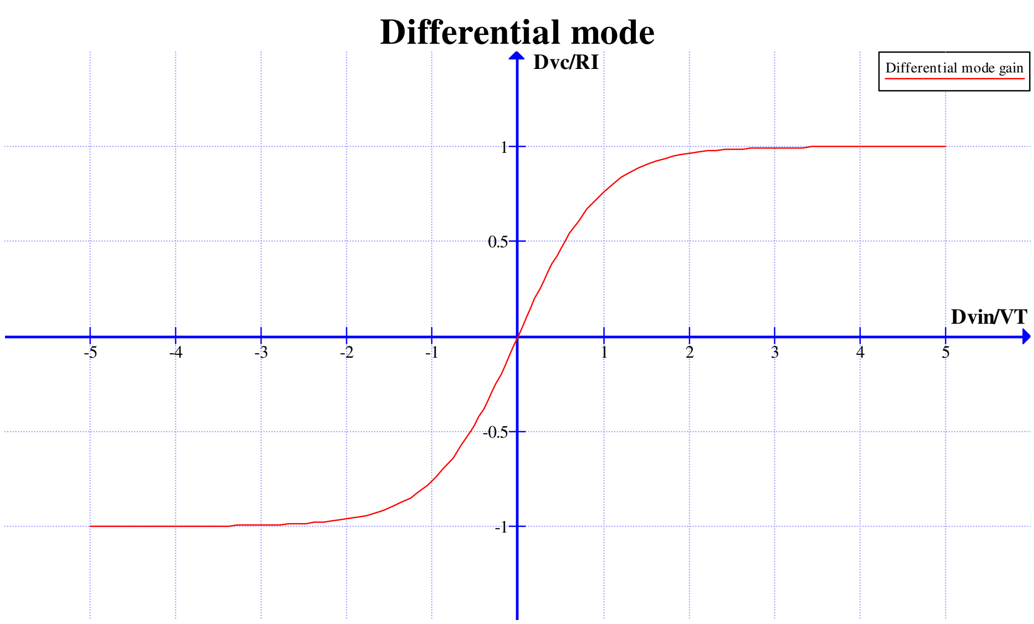
$$R_C = \frac{R_{C1} + R_{C2}}{2}$$
$$\Delta R_C = \frac{R_{C1} - R_{C2}}{2}$$

$$v_{C1}-v_{C2}=\alpha\left[R_{C1}\,i_{E1}-R_{C2}\,i_{E2}\right]$$
$$=\alpha\,R_C\left[\left(i_{E1}-i_{E2}\right)+\frac{\Delta R_C}{2R_C}\left(i_{E1}+i_{E2}\right)\right]$$

$$v_{C1}-v_{C2}=\alpha\,I\,R_C\left[\frac{\left(i_{E1}-i_{E2}\right)}{I}+\frac{\Delta R_C}{2R_C}\right]$$
$$=\alpha\,I\,R_C\left\{\frac{1-\exp\left[\left(v_{B2}-v_{B1}\right)/V_T\right]}{1+\exp\left[\left(v_{B2}-v_{B1}\right)/V_T\right]}+\frac{\Delta R_C}{R_C}\right\}$$
$$=\alpha\,I\,R_C\left\{\tanh\left[\left(v_{B1}-v_{B2}\right)/V_T\right]+\frac{\Delta R_C}{R_C}\right\}$$

$$v_{C1}-v_{C2}=\alpha\,I\,R_C\left[\frac{\left(i_{E1}-i_{E2}\right)}{I}+\frac{\Delta R_C}{2R_C}\right]$$
$$=\alpha\,I\,R_C\left\{\frac{1-\exp\left[\left(v_{B2}-v_{B1}\right)/V_T\right]}{1+\exp\left[\left(v_{B2}-v_{B1}\right)/V_T\right]}+\frac{\Delta R_C}{R_C}\right\}$$
$$=\alpha\,I\,R_C\left\{\tanh\left[\left(v_{B1}-v_{B2}\right)/V_T\right]+\frac{\Delta R_C}{R_C}\right\}$$

Matching ideale fra le res. di collettore: $\Delta R_C = 0$



$$\frac{\Delta v}{V_T}\ll 1 \rightarrow tanh\frac{\Delta v}{V_T}\approx\frac{\Delta v}{V_T}\rightarrow \text{Risposta lineare ai piccoli segnali!}$$

$$v_{C1} - v_{C2} \approx \frac{\alpha I R_C}{V_T}(v_{B1} - v_{B2}) + \alpha I \Delta R_C$$

Guadagno di modo differenziale:

$$G_{diff} \simeq \frac{IR_C}{V_T}$$

$\alpha I \Delta R_C \simeq I \Delta R_C$ = tensione di *offset*

$\rightarrow$ Necessita' di compensarla

Varie tecniche di compensazione (v. amplificatori operazionali)

Tensione differenziale di uscita:

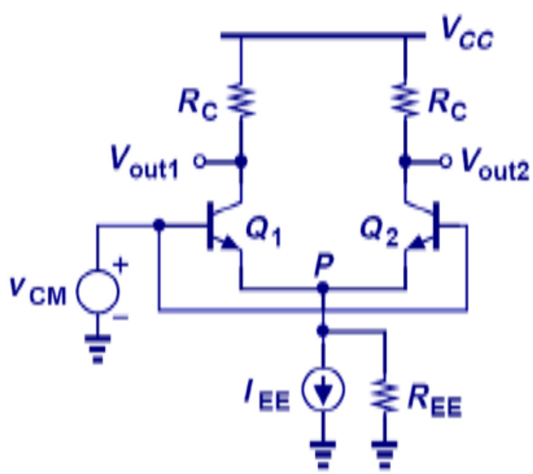
$\propto$ Tensione differenziale di ingresso

$\rightarrow$ Indipendente da tensione di modo comune in ingresso

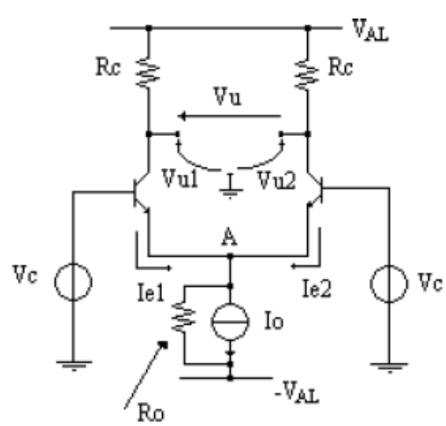
Es.: Aggiungendo V_{MC} a entrambi gli ingressi la tensione differenziale di uscita non cambia

Proprieta' legata alla scelta di un gen. ideale di corrente collegato agli emettitori

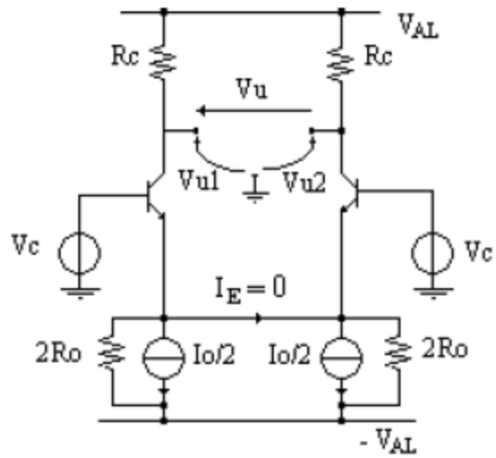
Se gen. di corrente collegato agli emitter $\neq$ ideale:
Tensione differenziale di uscita dipende anche da V_{MC}
$\rightarrow$ 2 diversi guadagni di tensione:
G_{diff}, G_{MC}
Guadagno di modo comune $\neq 0 \rightarrow$ Problema



Tensione di modo comune:
Applicata ai due ingressi



Circuito equivalente:



Guadagno di modo comune in caso di perfetta simmetria:

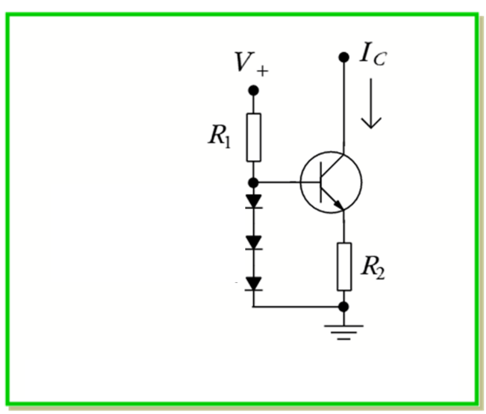
$$A_c = \frac{V_{u1}}{V_c} = \frac{V_{u2}}{V_c} = -\frac{\alpha R_C}{2R_0} \cong -\frac{R_C}{2R_0}$$

Per ridurlo R_0 molto grande → Non pratico

Miglioramenti:

a) Generatore di corrente con transistor

Es semplice:



$V_{diodi} \simeq 1.8V \rightarrow V_2 \simeq 1.2V \rightarrow I_E = \frac{V_{diodi} - V_{BE}}{R_2} \simeq \frac{1.2}{R_2} \simeq I_C$

Res. dinamica su collettore $\sim r_0 \sim 100 - 200 K\Omega$

Rapporto di reiezione al modo comune ($CMRR$):

$$CMRR = \frac{G_{diff}}{G_{comm}} \simeq \frac{IR_C}{V_T} \frac{2r_0}{R_C} = \frac{2Ir_0}{V_T}$$

Es:

$I = 1\ mA, r_0 = 100\ K\Omega$

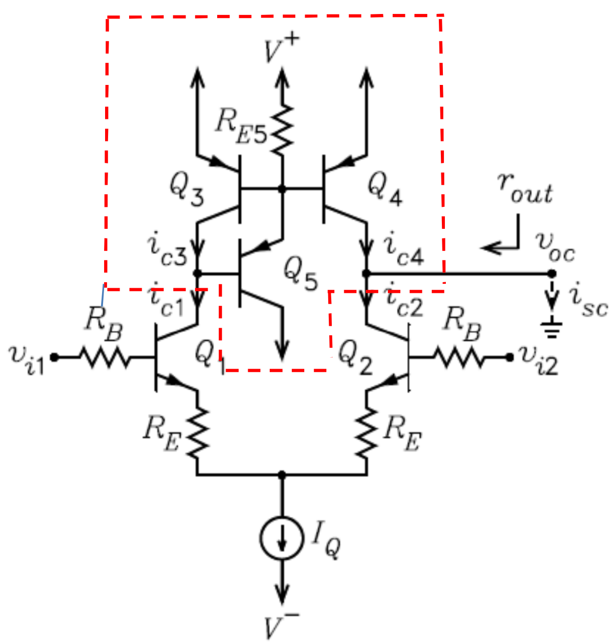
$$\rightarrow CMRR \simeq \frac{2Ir_0}{V_T} = \frac{210^{-3}10^5}{2610^{-3}} \sim 7.710^3 \sim 80dB$$

Confronto con resistenza R_0 :

$$V_{EE} = -12V \rightarrow \frac{12}{R_0} = 1mA \rightarrow R_0 \sim 10K$$

$\rightarrow CMRR \simeq 770$

b) Carico attivo



Area fra linee rosse:

Current mirror (con compensazione della corrente di base)

$\rightarrow$ Corrente di collettore fissa $\rightarrow$ Res. dinamica (molto) grande