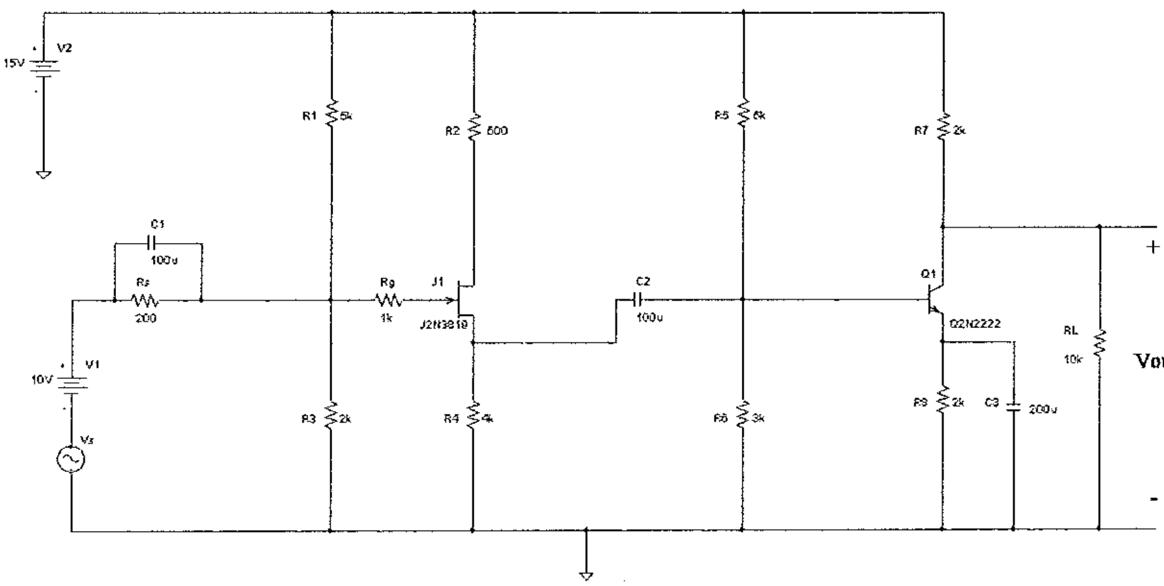
## Prova scritta di Elettronica –
## Corso di Laurea in Ingegneria delle Telecomunicazioni - 20 Luglio 2011

1. Si consideri un amplificatore di tensione con $A_v = 2000$, $R_{in} = 0.5$ MΩ, $R_{out} = 80$ Ω. Si reazioni in modo da ottenere un amplificatore con impedenza di ingresso di 2 KΩ (con una tolleranza del 10%) e impedenza di uscita minore di 2 Ω. Una volta scelta e dimensionata la rete di reazione, si calcolino le resistenze di ingresso e uscita così ottenute.
2. Facendo riferimento al modello di Ebers e Moll del transistore bipolare, ricavare l'espressione della corrente di emettitore nel caso in cui $I_B$=0 e $V_{BE}$<0 in funzione dei parametri caratteristici del modello.
3. Dato l'amplificatore disegnato in figura, calcolare:

- Il punto di riposo dei 2 transistori e i parametri per piccolo segnale (*punteggio 5/30*);
- L'amplificazione Vu/Vs a centrobanda (*punteggio 4/30*);
- Il limite inferiore e il limite superiore di banda (*punteggio 8/30*);
    - o Il JFET è un 2N3819 con rd →∞
    - o Il BJT è un QN2222 con hoe = 0
    - o Il BJT si consideri resistivo.



$A_V = 2000$

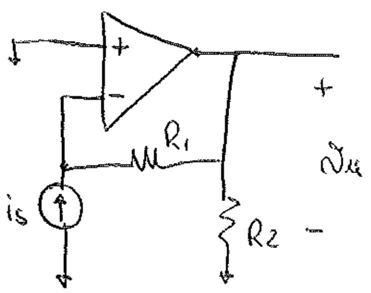
$R_{in} = 0.5\,M\Omega$

$R_{OUT} = 80\,\Omega$

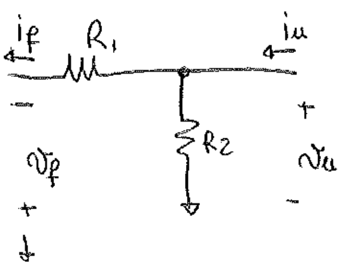
$R_{IF} = 2\,k\Omega \quad \pm 10\%$

$R_{OF} < 2\,\Omega$

È necessario realizzare una reazione con inserzione di corrente e prelievo di tensione



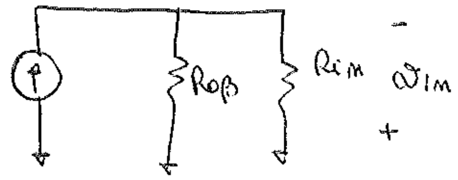

rete per $\beta$

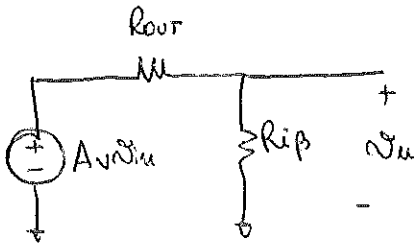



$$\begin{cases} i_f = \beta v_u + \dfrac{v_f}{R_{o\beta}} \\ i_u = \dfrac{v_u}{R_{i\beta}} + v_f k_1 \end{cases}$$

$$\beta = \left.\frac{i_f}{v_u}\right|_{v_f=0} = \frac{1}{R_1} \; ; \quad R_{o\beta} = \left.\frac{v_f}{i_f}\right|_{v_u=0} = R_1 \; ; \quad R_{i\beta} = \left.\frac{v_u}{i_u}\right|_{v_f=0} = R_1 // R_2$$

rete per Ae



$$A_e = -(R_{in}//R_{o\beta}) \cdot A_v \cdot \frac{R_{i\beta}}{R_{i\beta}+R_{OUT}}$$

Hp: $\beta A_e \gg 1$

$$R_{iF} = \frac{R_{o\beta}//R_{in}}{(1-\beta A_e)} \simeq \frac{R_{o\beta}//R_{in}}{-\beta A_e} = \frac{1}{\frac{1}{R_1} \cdot A_v \cdot \frac{R_{i\beta}}{R_{i\beta}+R_{OUT}}} = \frac{R_1(R_{i\beta}+R_{OUT})}{A_v R_{i\beta}}$$

$$R_{oF} = \frac{R_{OUT}//R_{i\beta}}{(1-\beta A_e)} \simeq \frac{R_{OUT}//R_{i\beta}}{-\beta A_e} = \frac{1}{\frac{(R_{in}//R_{o\beta}) \cdot A_v}{R_1 \cdot R_{OUT}}} = \frac{R_1 \cdot \overset{80}{R_{OUT}}}{(R_{in}//R_{o\beta}) \cdot \underset{2000}{A_v}}$$

$R_{oF} < 2\,\Omega$

è soddisfatta se

$$R_{oF} = \frac{R_1}{R_{in}//R_{o\beta}} \cdot \frac{1}{25} < 2$$

$$\frac{R_1}{R_{in}//R_{o\beta}} < 50$$

$$R_{in}//R_{o\beta} > \frac{1}{50} R_1$$

$$R_{in}//R_1 > \frac{1}{50} R_1$$

$$50 \frac{R_{in} \cdot R_1}{R_{in}+R_1} > R_1$$

$$50 R_{in} \cdot R_1 > R_1^2 + R_1 R_{in}$$

$$\boxed{49 R_{in} > R_1}$$

$R_{IF} = 2\,K\Omega$

$$R_{IF} = \frac{R_1\,(R_1//R_2 + R_{OUT})}{A_V \cdot (R_1//R_2)} = 2000$$

Poniamo $R_1//R_2 = 100\,\Omega$

$$\frac{R_1}{A_V} \cdot \frac{100+80}{100} = \frac{R_1}{A_V} \cdot 1.8 = 2000 \Rightarrow R_1 = \frac{2000\,A_V}{1.8} = 2.2\,M\Omega$$

$R_2 \cong 100\,\Omega$

calcolo $\beta A_e$

$$\frac{1}{R_1}\left(R_{in}//R_{o\beta}\right) A_V \cdot \frac{R_{i\beta}}{R_{i\beta}+R_{OUT}} = \frac{1}{2.2\times10^6}\left(0.5\times10^6//2.2\times10^6\right) \cdot 2000 \cdot \frac{100}{180}$$

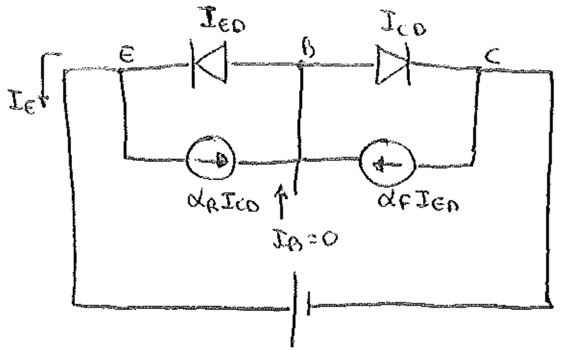
$\cong 205 \gg 1$

calcolo per verifica

$$R_{IF} = \frac{R_1//R_{in}}{1-\beta A_e} = \frac{2.2\times10^6//0.5\times10^6}{1+205} \cong 1.98\,K\Omega \quad \text{ok!}$$

$$R_{OF} = \frac{R_{OUT}//R_1//R_2}{1-\beta A_e} = \frac{80//100}{1+205} \cong 0.22\,\Omega \quad \text{ok!}$$

(a)




$V_{CE} < 0$

quindi $I_{ED} = -I_{ES}$

$$I_E = I_{ED} - \alpha_R I_{CD} = -I_{ES} - \alpha_R I_{CD}$$

$$= -I_{CD} + \alpha_F I_{ED} = -I_{CD} - \alpha_F I_{ES}$$

da cui

$$(1 - \alpha_F) I_{ES} = (1 - \alpha_R) I_{CD}$$

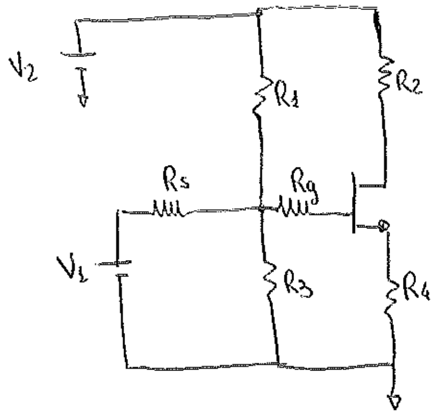
$$I_{CD} = \frac{(1 - \alpha_F)}{(1 - \alpha_R)} I_{ES}$$

$$I_E = -I_{ES} \left[ 1 + \frac{\alpha_R (1 - \alpha_F)}{1 - \alpha_R} \right] = -I_{ES} \left[ \frac{1 - \alpha_R + \alpha_R - \alpha_R \alpha_F}{1 - \alpha_R} \right]$$

$$\boxed{I_E = -I_{ES} \frac{1 - \alpha_R \alpha_F}{1 - \alpha_R}}$$

PUNTO DI RIPOSO JFET






PRINCIPIO SOVRAPPOSIZIONE DEGLI EFFETTI

$$V_G = V_{G1} + V_{G2}$$

$$V_{G1} = V_1 \cdot \frac{R_1 // R_3}{R_S + R_1 // R_3} = 8.77\,V$$

$$V_{G2} = V_2 \cdot \frac{R_3 // R_S}{R_1 + R_3 // R_S} = 0.53\,V$$

$$V_G = V_{G1} + V_{G2} = 9.3\,V$$

$$V_{GS} = V_G - V_S$$

$$V_{GS} = V_G - R_4 I_{DS}$$

$$I_{DS} = \frac{V_G - V_{GS}}{R_4}$$

$$\begin{cases} V_{GS_1} = 0 \\ V_{GS_2} = -3\,V \end{cases} \qquad \begin{matrix} I_{DS_1} = 2.325\,mA \\ I_{DS_2} = 3.075\,mA \end{matrix}$$

$$V_{GS} \cong -1.6\,V \qquad I_{DS} \cong 2.725\,mA$$

$$V_{DS} = V_2 - (R_2 + R_4) I_{DS} = 15 - (0.5 + 4) \cdot 2.725 = 2.74\,V$$

verifica JFET in saturazione

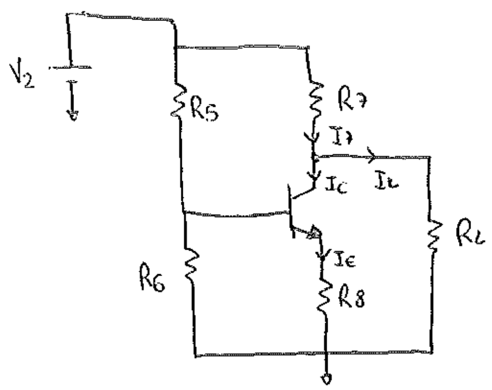
$$V_{GS} > V_{GSoff} \qquad -1.6 > -3 \qquad \text{ok!}$$

$$V_{DS} > V_{GS} - V_{GSoff} = -1.6 + 3 = 1.4\,V$$

$$2.74 > 1.4 \qquad \text{ok!}$$

# PUNTO DI RIPOSO BJT






Hp. PARTITORE PESANTE

$$V_B = \frac{R_6}{R_5+R_6} \cdot V_2 = 5.625\,V$$

$$V_{BE} = V_B - V_E \Rightarrow V_E = V_B - V_{BE} = 4.925\,V$$

$$I_E = \frac{V_E}{R_8} \cong 2.46\,mA$$

$$I_C \cong I_E \cong 2.46\,mA$$

$$\begin{cases} I_7 = I_C + I_L \\ I_L = \frac{V_C}{R_L} \\ I_7 = \frac{V_2 - V_C}{R_7} \end{cases}$$

$$I_C + \frac{V_C}{R_L} = \frac{V_2 - V_C}{R_7}$$

$$R_L R_7 I_C + R_7 V_C = (V_2 - V_C) R_L$$

$$V_C = \frac{R_L V_2 - R_L R_7 I_C}{R_7 + R_L} \cong \frac{(10 \times 15) - (10 \times 2 \times 2.46)}{2+10} = 8.4\,V$$

$$V_{CE} = V_C - V_E \cong 3.475\,V$$

$$I_7 = \frac{V_2 - V_C}{R_7} = 3.3\,mA$$

$$I_L = \frac{V_C}{R_L} = 0.84\,mA$$

VERIFICA HP. P.P.

$$h_{FE} \cong 160$$

$$I_B = \frac{I_C}{h_{FE}} \cong 15\,\mu A$$

$$I_{R6} = \frac{V_B}{R_6} \cong 1.875\,mA$$

$I_B \ll I_{R5}, I_{R6}$ OK!

$$I_{R5} = \frac{V_2 - V_B}{R_5} \cong 1.875\,mA$$

# PARAMETRI PICCOLO SEGNALE



- JFET

$g_m \cong 3.4\ mS$ (curva $g_m$ in funzione di $V_{GS}$)

$C_{iss} \cong 2.7\ pF$

$C_{rss} \cong 1.4\ pF$

$C_{GD} = C_{rss} \cong 1.4\ pF$

$C_{GS} = C_{iss} - C_{rss} \cong 1.3\ pF$

- BJT

$h_{fe} = \frac{50+300}{2} = 175$

$h_{ie} @ 1\,mA = \frac{2+8}{2} = 5\ k\Omega$

$r_{b'e} @ 1\,mA = \frac{V_T \cdot h_{fe}}{I_C @ 1\,mA} = 4.55\ k\Omega$

$r_{bb'} = h_{ie} - r_{b'e} = 450\ \Omega$

$r_{b'e} = \frac{V_T \cdot h_{fe}}{I_C} \cong 1.85\ k\Omega$

$h_{ie} = r_{b'e} + r_{bb'} = 2.3\ k\Omega$

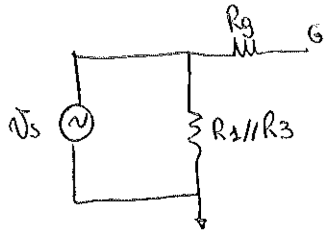
$f_T \cong 160\ MHz$

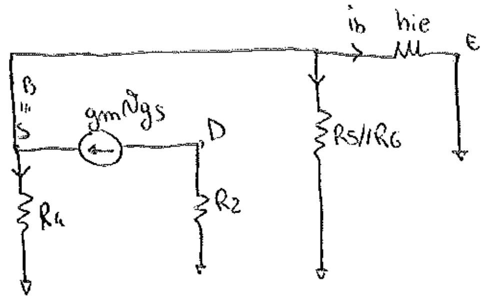
$g_m^{BJT} = \frac{I_C}{V_T} = 94.62\ mS$

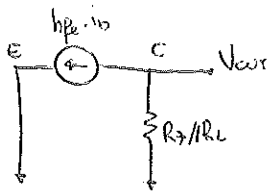
$V_{CB} = V_{CE} - V_{BE} = 2.775\ V$

# GUADAGNO A CENTRO BANDA



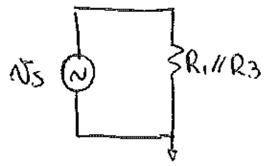


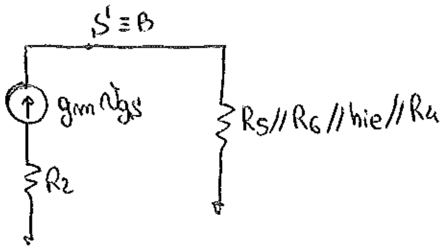



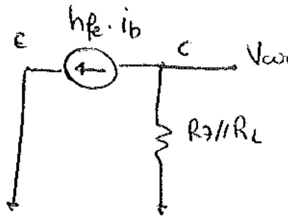




$$V_{OUT} = -R_7 // R_L \, h_{fe} \cdot i_b$$

$$i_b = \frac{V_B}{h_{ie}} = \frac{V_{S'}}{h_{ie}}$$




$$v_B = v_{S'} = R_5 // R_6 // h_{ie} // R_4 \cdot g_m \, v_{gs'}$$

$$v_{gs} = v_g - v_{S'}$$

$$v_g = v_s$$

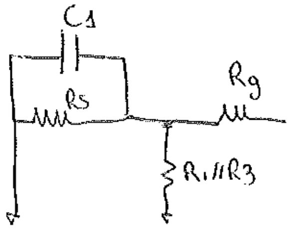
$$v_{S'} = R_5 // R_6 // h_{ie} // R_4 \; g_m \left( v_g - v_{S'} \right)$$

$$v_{S'} = \frac{R_5 // R_6 // h_{ie} // R_4 \; g_m}{1 + R_5 // R_6 // h_{ie} // R_4 \; g_m} \, v_s$$

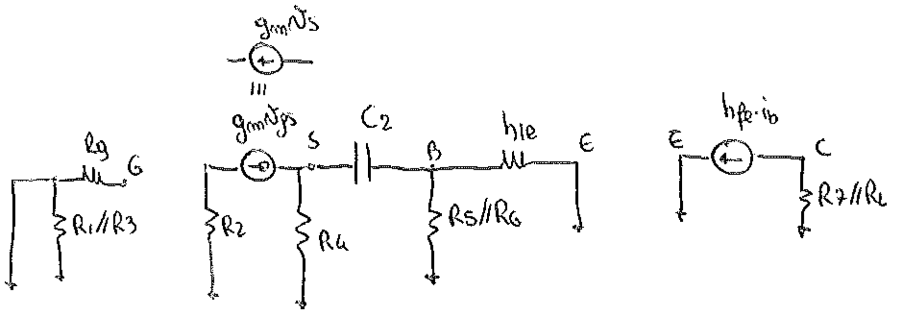
$$A_{CB} = \frac{v_{OUT}}{v_s} = -R_7 // R_L \cdot \frac{h_{fe}}{h_{ie}} \cdot \frac{R_5 // R_6 // h_{ie} // R_4 \; g_m}{1 + R_5 // R_6 // h_{ie} // R_4 \; g_m} \cong -93.32$$

LIMITE INFERIORE DI BANDA

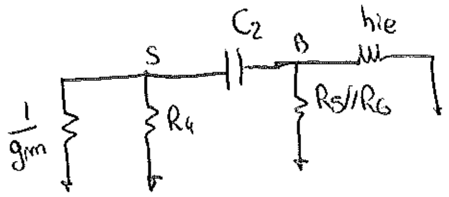




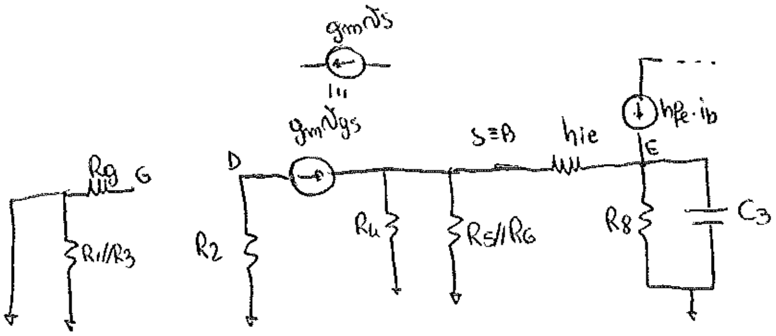

$$R_{VC1}\Big|_{C_2,C_3\ \text{corto}} = R_S // R_1 // R_3 \cong 0.175\ k\Omega$$



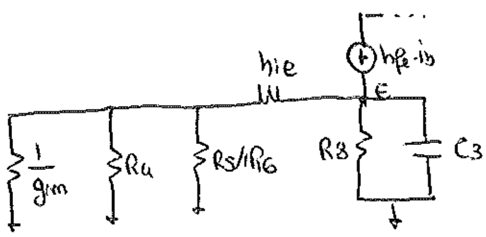

$v_g = 0$



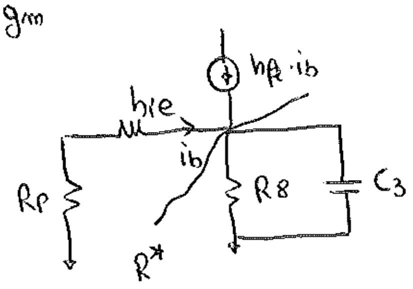

$$R_{VC2}\Big|_{C_1,C_3\ \text{corto}} = \left(\frac{1}{g_m} // R_4\right) + \left(h_{ie} // R_5 // R_6\right) \cong 1.31\ k\Omega$$

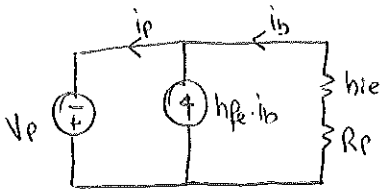



$v_g = 0$




$$R_P = \frac{1}{g_m} // R_4 // R_5 // R_6 \cong 0.239\ k\Omega$$






$$i_p = i_b + h_{fe} \cdot i_b = (1 + h_{fe}) i_b$$

$$V_p = (h_{ie} + R_p) \cdot i_b$$

$$R^* = \frac{V_p}{i_p} = \frac{R_p + h_{ie}}{1 + h_{fe}} = \frac{0.239 + 2.3}{1 + 175} = 14.4\ \Omega$$

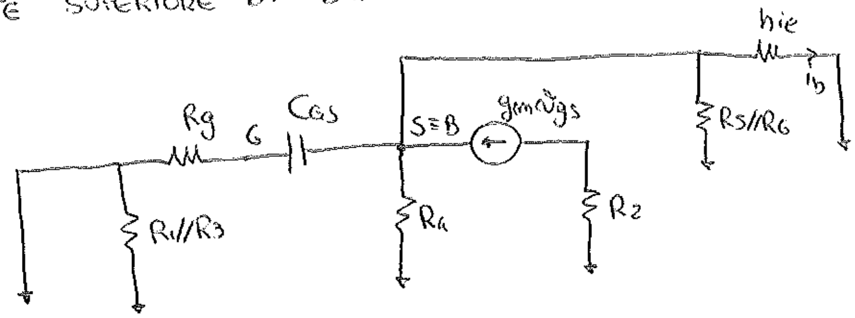
$$R_{VC3} = R_8 // R^* = 0.0143\ k\Omega$$

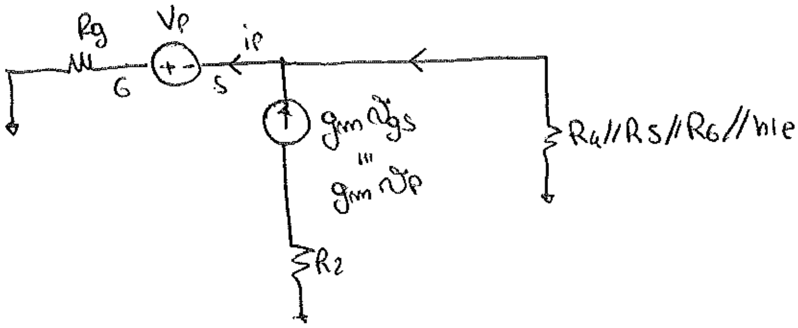
$$f_L = \frac{1}{2\pi} \left[ \frac{1}{C_1 \cdot R_{VC1}} + \frac{1}{C_2 \cdot R_{VC2}} + \frac{1}{C_3 \cdot R_{VC3}} \right] =$$

$$= \frac{1}{2\pi} \left[ \frac{1}{100 \times 10^{-6} \times 0.175 \times 10^3} + \frac{1}{100 \times 10^{-6} \times 1.31 \times 10^3} + \frac{1}{200 \times 10^{-6} \times 0.0143 \times 10^3} \right] \approx 66\ Hz$$

LIMITE SUPERIORE DI BANDA



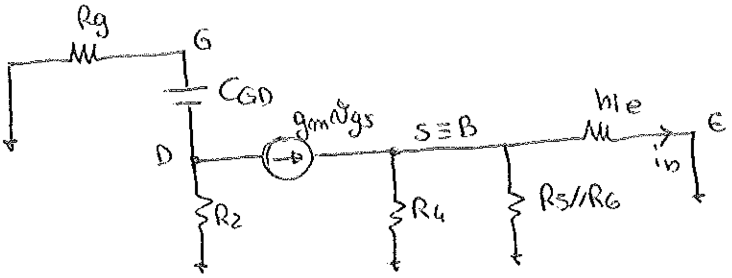


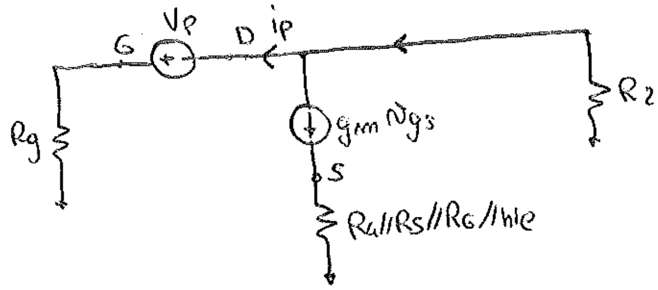




$$V_p = R_g \cdot i_p + R_4 // R_5 // R_6 // h_{ie} \, (i_p - g_m V_p)$$

$$V_p (1 + g_m \, R_4 // R_5 // R_6 // h_{ie}) = (R_g + R_4 // R_5 // R_6 // h_{ie}) \cdot i_p$$

$$R_{VCgs} = \frac{V_p}{i_p} = \frac{R_g + \overbrace{R_4 // R_5 // R_6 // h_{ie}}^{0.821\,k\Omega}}{1 + g_m \, R_4 // R_5 // R_6 // h_{ie}} \cong 480\,\Omega$$




$$V_p = R_g \cdot i_p + R_2 \left( i_p + g_m v_{gs} \right)$$

$$v_{gs} = R_g \cdot i_p - R_4 // R_5 // R_6 // h_{ie} \; g_m v_{gs}$$

$$v_{gs} \left( 1 + g_m \, R_4 // R_5 // R_6 // h_{ie} \right) = R_g \cdot i_p$$

$$v_{gs} = \frac{R_g}{1 + g_m \, R_4 // R_5 // R_6 // h_{ie}} \cdot i_p$$

$$V_p = R_g \, i_p + R_2 \cdot i_p + g_m \, R_2 \frac{R_g}{1 + g_m \, R_4 // R_5 // R_6 // h_{ie}} \cdot i_p$$

$$R_{VCGD} = \frac{V_p}{i_p} = R_g + R_2 + g_m \frac{R_2 \, R_g}{1 + g_m \, R_4 // R_5 // R_6 // h_{ie}} \cong 1.95 \, k\Omega$$

$$f_H = \frac{1}{2\pi \left[ C_{GS} \cdot R_{VCGS} + C_{GD} \cdot R_{VCGD} \right]} = \frac{1}{2\pi \left[ 1.3 \times 10^{-12} \times 0.48 \times 10^{3} + 1.4 \times 10^{-12} \times 1.95 \times 10^{3} \right]} \cong 47.5 \, MHz$$