ΒΑΣΙΚΕΣ ΕΞΙΣΩΣΕΙΣ ΗΛΕΚΤΡΟΝΙΚΗΣ ΙΙΙ

Πολυβάθμιοι ενισχυτές

$$A_v = \frac{e_{\text{out}}}{V_S} = \prod_{i=1}^{n} A_i = \frac{R_{in,1}}{R_{in,1}+R_S} \cdot \frac{R_{in,2}}{R_{in,2}+R_{out,1}} \cdot \ldots \cdot \frac{R_L}{R_L+R_{out,n}}$$

Με n όμοιες βαθμίδες: $\omega_{nL} = \dfrac{\omega_0}{\sqrt{2^{1/n}-1}}$. Με n βαθμίδες με $f_{Lj},\ j=1,\ldots,n$: $f_{nL} \approx 1.1\sqrt{\sum_{j=1}^{n} f_{Lj}^2}$

Με n όμοιες βαθμίδες: $\omega_{nH} = \omega_0\sqrt{2^{1/n}-1}$. Με n βαθμίδες με $f_{Hj},\ j=1,\ldots,n$: $f_{nH} \approx \left(1.1\sqrt{\sum_{j=1}^{n} f_{Hj}^2}\right)^{-1}$

Ζεύγος κοινού συλλέκτη - κοινής βάσης:

$$\frac{V_o}{V_{\text{sig}}} = \frac{1}{2}\left(\frac{R_{\text{in}}}{R_{\text{in}}+R_{\text{sig}}}\right)(g_m R_L) \qquad R_{\text{in}} = 2r_\pi$$

$$f_{P1} = \frac{1}{2\pi\left(\frac{C_\pi}{2}+C_\mu\right)(R_{\text{sig}} \parallel 2r_\pi)} \qquad f_{P2} = \frac{1}{2\pi C_\mu R_L} \qquad f_H \cong \frac{1}{\sqrt{\frac{1}{f_{P1}^2}+\frac{1}{f_{P2}^2}}}$$

Ζεύγος κοινής πηγής - κοινής πύλης (κασκοδική συνδεσμολογία):

$$R_{\text{out}} = r_{o2} + [1+(g_{m2}+g_{mb2})\, r_{o2}]\, r_{o1} \qquad A_v = -A_0^2\frac{R_L}{R_L+A_0 r_0} \qquad f_H \cong \frac{1}{2\pi\tau_H}$$

$$R_{gd1} = (1+g_{m1}R_{d1})\,R_{\text{sig}} + R_{d1} \qquad \tau_H = R_{\text{sig}}\left[C_{gs1}+C_{gd1}(1+g_{m1}R_{d1})\right] + R_{d1}\left(C_{gd1}+C_{db1}+C_{gs2}\right) + (R_L \parallel R_{\text{out}})\,(C_L+C_{gd2})$$

Ζεύγος κοινού εκπομπού - κοινής βάσης (κασκοδική συνδεσμολογία):

$$A_M = -\frac{r_\pi}{r_\pi+r_x+R_{\text{sig}}}\, g_m\,(\beta r_0 \parallel R_L) \qquad R_{c1} = r_{01} \parallel \left[r_{e2}\left(\frac{r_{o2}+R_L}{r_{o2}+{}^{R_L}\!/_{(\beta_2+1)}}\right)\right]$$

$$R'_{\text{sig}} = r_{\pi1} \parallel (r_{x1}+R_{\text{sig}}) \qquad \tau_H = C_{\pi1}R_{\pi1} + C_{\mu1}R_{\mu1} + (C_{cs1}+C_{\pi2})\,R_{c1} + (C_L+C_{cs2}+C_{\mu2})\,(R_L \parallel R_{\text{out}})$$

$$R_{\mu1} = R'_{\text{sig}}\,(1+g_{m1}R_{c1}) + R_{c1} \qquad f_H \simeq \frac{1}{2\pi\tau_H}$$

Τελεστικός ενισχυτής MOS δύο βαθμίδων:

$$A_v = -g_{m1}\,(r_{ds2} \parallel r_{ds4}) \qquad g_{m1} = \sqrt{2\mu_p C_{ox}\left(\frac{W}{L}\right)_1 I_{D1}} = \sqrt{2\mu_p C_{ox}\left(\frac{W}{L}\right)_1 \frac{I_{bias}}{2}}$$

$$R_B = \frac{2}{\sqrt{2\mu_n C_{ox}\,({}^{W}\!/_{L})_{12}\, I_B}}\left(\sqrt{\frac{({}^{W}\!/_{L})_{12}}{({}^{W}\!/_{L})_{13}}}-1\right)$$

$$g_{m12} = \frac{2}{R_B}\left(\sqrt{\frac{({}^{W}\!/_{L})_{12}}{({}^{W}\!/_{L})_{13}}}-1\right) \qquad g_{mi} = g_{m12}\sqrt{\frac{I_{Di}\,({}^{W}\!/_{L})_i}{I_B\,({}^{W}\!/_{L})_{12}}} \qquad g_{mi} = g_{m12}\sqrt{\frac{\mu_p I_{Di}\,({}^{W}\!/_{L})_i}{\mu_n I_B\,({}^{W}\!/_{L})_{12}}}$$

$$C_1 = C_{gd4}+C_{db4}+C_{gd2}+C_{gs6} \qquad C_2 = C_{db6}+C_{db7}+C_{gd7}+C_L$$

$$\omega_Z = \frac{G_{m2}}{C_C} \qquad \omega_{P1} = \frac{1}{C_1R_1+C_2R_2+C_C\,(G_{m2}R_2R_1+R_1+R_2)} \cong \frac{1}{R_1C_CG_{m2}R_2}$$

$$\omega_{P2} = \frac{G_{m2}C_C}{C_1C_2+C_C\,(C_1+C_2)} \qquad \omega_t = (G_{m1}R_1G_{m2}R_2)\,\omega_{P1}$$

Επιλογή C_C ώστε $\omega_t < \omega_Z < \omega_{P2}$

$$\text{PSRR} = g_{mN}\,(r_{oP} \parallel r_{oN}) \qquad \text{SR} \equiv \left.\frac{\mathrm{d}V_{\text{out}}}{\mathrm{d}t}\right|_{\max} = \frac{I_{SS}}{C_L}$$

$$\text{GB} = A_v(0)\cdot|p_1| = (g_{m1}g_{m2}R_IR_{II})\cdot\left(\frac{1}{g_{m2}R_IR_{II}C_C}\right) = \frac{g_{m1}}{C_C}$$

$$\text{PM} = \text{Arg}\,[AB] = \pm180^\circ - \arctan\left(\frac{\omega}{|p_1|}\right) - \arctan\left(\frac{\omega}{|p_2|}\right) - \arctan\left(\frac{\omega}{Z}\right)$$

Για περιθώριο φάσης (PM) 45° και $Z \geqslant 10\cdot\text{GB}$: $|p_2| \geqslant 1.22\cdot\text{GB}$

Για περιθώριο φάσης (PM) 60° και $Z \geqslant 10\cdot\text{GB}$: $|p_2| \geqslant 2.22\cdot\text{GB}$

$$Z = \frac{1}{C_C\left(\frac{1}{g_{m2}}-R_Z\right)}$$

Τελεστικός ενισχυτής με είσοδο n-MOS

$$\max(V_{\text{in}}) = V_{DD} - \sqrt{\frac{I_5}{\beta_3}} - \max(|V_{T03}|) + \min(V_{T01}) \qquad \min(V_{\text{in}}) = V_{SS} + \sqrt{\frac{I_5}{\beta_1}} + \max(V_{T01}) + V_{DS5_{\text{sat}}} \qquad V_{DS_{\text{sat}}} = \sqrt{\frac{2I_{DS}}{\beta}}$$

Τελεστικός ενισχυτής με είσοδο p-MOS

$$\max(V_{\text{in}}) = V_{DD} - \sqrt{\frac{I_5}{\beta_1}} - V_{DS5_{\text{sat}}} - \max(|V_{T01}|) \qquad \min(V_{\text{in}}) = V_{SS} + \sqrt{\frac{I_5}{\beta_3}} + \max(V_{T03}) - \min(|V_{T01}|)$$

Σχεδίαση τελεστικού ενισχυτή με είσοδο n-MOS

$$\text{SR} = \frac{I_5}{C_C} \qquad A_{v1} = \frac{-g_{m1}}{g_{ds2} + g_{ds4}} = \frac{-2g_{m1}}{I_5 \cdot (\lambda_2 + \lambda_4)} \qquad A_{v2} = \frac{-g_{m6}}{g_{ds6} + g_{ds7}} = \frac{-g_{m6}}{I_6 \cdot (\lambda_6 + \lambda_7)}$$

$$\text{GB} = \frac{g_{m1}}{C_C} \qquad p_2 = \frac{-g_{m6}}{C_L} \qquad Z = \frac{g_{m6}}{C_C} \qquad \beta = k' \frac{W}{L} \cong \mu_0 C_{ox} \frac{W}{L} \;\; (\text{A}/\text{V}^2)$$

$$C_C > 0.22 C_L \qquad I_5 = \text{SR} \cdot C_C \qquad S_3 = \left(\frac{W}{L}\right)_3 = \frac{I_5}{k_3' \left[V_{DD} - \max(V_{\text{in}}) - \max(|V_{T03}|) + \min(V_{T01})\right]^2}$$

$$\frac{g_{m3}}{2C_{gs3}} > 10 \cdot \text{GB} \qquad g_{m1} = \text{GB} \cdot C_C \Longrightarrow S_1 = S_2 = \frac{g_{m2}^2}{k_2' I_5}$$

$$V_{DS5_{\text{sat}}} = \min(V_{\text{in}}) - V_{SS} - \sqrt{\frac{I_5}{\beta_1}} - \max(V_{T01}) \geqslant 100\text{mV} \qquad S_5 = \frac{2I_5}{k_5' V_{DS5_{\text{sat}}}^2}$$

$$g_{m6} = 2.2 g_{m2} \left({}^{C_L}/{}_{C_C}\right) \qquad S_6 = S_4 \frac{g_{m6}}{g_{m4}} \qquad I_6 = \frac{g_{m6}^2}{2k_6' S_6}$$

$$S_6 = \frac{g_{m6}}{k_6' V_{DS6_{\text{sat}}}} \qquad V_{DS6} = \min(V_{DS6}) = V_{DS6_{\text{sat}}} = V_{DD} - \max(V_{\text{out}}) \qquad S_7 = S_5 \frac{I_6}{I_5}$$

$$A_v = \frac{2g_{m2} g_{m6}}{I_5 (\lambda_2 + \lambda_4) I_6 (\lambda_6 + \lambda_7)} \qquad P_{\text{diss}} = (I_5 + I_6) \cdot (V_{DD} + |V_{SS}|)$$

Κυκλώματα ανόρθωσης

Zener diode: $V_Z = V_{Z0} + r_Z \cdot I_Z$

Ημιανορθωτής:

$$P_{\text{DC}} = I_{\text{DC}}^2 R = \frac{I_m^2}{\pi^2} R \qquad P_{\text{AC}} = I_{\text{rms}}^2 R = \frac{I_m^2}{4} R \qquad n = \frac{P_{\text{DC}}}{P_{\text{AC}}} 100\% = 40.6\% \qquad r = \frac{\sqrt{I_{\text{rms}}^2 - I_{\text{DC}}^2}}{I_{\text{DC}}} 100\% = 121\%$$

Πλήρης ανορθωτής:

$$P_{\text{DC}} = I_{\text{DC}}^2 R = \frac{4I_m^2}{\pi^2} R \qquad P_{\text{AC}} = I_{\text{rms}}^2 R = \frac{I_m^2}{2} R \qquad n = \frac{P_{\text{DC}}}{P_{\text{AC}}} 100\% = 81.2\% \qquad r = \frac{\sqrt{I_{\text{rms}}^2 - I_{\text{DC}}^2}}{I_{\text{DC}}} 100\% = 48\%$$

Ημιανορθωτής με φίλτρο πυκνωτή:

$$V_{\text{DC}} \equiv V_o = V_p - \frac{1}{2} V_r \qquad i_{D,\text{av}} = I_L \left(1 + \pi \sqrt{{}^{2V_p}/{}_{V_r}}\right) \qquad i_{D,\text{max}} = I_L \left(1 + 2\pi \sqrt{{}^{2V_p}/{}_{V_r}}\right)$$

$$V_r = \frac{V_p}{fCR} = \frac{I_L}{fC} \qquad r = \frac{V_{\text{AC,rms}}}{V_{\text{DC}}} = \frac{V_r}{2\sqrt{3} V_{\text{DC}}} \approx \frac{1}{2\sqrt{3} fCR}$$

Πλήρης ανορθωτής με φίλτρο πυκνωτή:

$$V_r = \frac{V_p}{2fCR} \qquad i_{D,\text{av}} = I_L \left(1 + \pi \sqrt{{}^{V_p}/{}_{2V_r}}\right) \qquad i_{D,\text{max}} = I_L \left(1 + 2\pi \sqrt{{}^{V_p}/{}_{2V_r}}\right)$$

$$r = \frac{V_{\text{AC,rms}}}{V_{\text{DC}}} = \frac{V_r}{2\sqrt{3} V_{\text{DC}}} \approx \frac{1}{4\sqrt{3} fCR}$$

Κυκλώματα αναφοράς

Πηγή Widlar:

$$V_T \cdot \ln\left(\frac{I_{\text{in}}}{I_{\text{out}}}\right) = I_{\text{out}} \cdot R_2 \qquad I_{\text{out}}R_2 + \sqrt{\frac{2I_{\text{out}}}{k'\,(W/L)_2}} - V_{ov1} = 0 \qquad \sqrt{I_{\text{out}}} = \frac{-\sqrt{\frac{2}{k'\,(W/L)_2}} - \sqrt{\frac{2}{k'\,(W/L)_2} + 4R_2V_{ov1}}}{2R_2}$$

Πηγή μεγίστου ρεύματος:

$$I_{\text{out}} = I_{\text{in}} \exp\left(-\frac{I_{\text{in}}R}{V_T}\right) \qquad R = \frac{V_T}{I_{\text{in}}} \ln\left(\frac{I_{\text{in}}}{I_{\text{out}}}\right) \qquad I_D = \frac{W}{L} I_t \exp\left(\frac{V_{GS} - V_t}{nV_T}\right) \cdot \left[1 - \exp\left(-\frac{V_{DS}}{V_T}\right)\right]$$

$$I_{\text{out}} \simeq \frac{W}{L} I_t \exp\left(\frac{V_{GS2} - V_t}{nV_T}\right) \simeq I_{\text{in}} \exp\left(-\frac{I_{\text{in}}R}{nV_T}\right) \qquad I_{\text{out}} = \frac{k'}{2}\left(\frac{W}{L}\right)_2 V_{ov2}^2 = \frac{k'}{2}\left(\frac{W}{L}\right)_2 (V_{ov1} - I_{\text{in}}R)^2$$

$$S_{V_{\text{sup}}}^{I_{\text{out}}} = \frac{V_{\text{sup}}}{I_{\text{out}}} \cdot \frac{\partial I_{\text{out}}}{\partial V_{\text{sup}}} \qquad S_{V_{\text{sup}}}^{I_{\text{out}}} = \left(\frac{1}{1 + \frac{I_{\text{out}}R_2}{V_T}}\right) \cdot \frac{V_{CC}}{I_{\text{in}}} \cdot \frac{\partial I_{\text{in}}}{\partial V_{CC}} = \left(\frac{1}{1 + \frac{I_{\text{out}}R_2}{V_T}}\right) S_{V_{CC}}^{I_{\text{in}}}$$