# ΒΑΣΙΚΕΣ ΕΞΙΣΩΣΕΙΣ ΗΛΕΚΤΡΟΝΙΚΗΣ ΙΙΙ

#### Πολυβάθμιοι ενισχυτές

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

Με 
$$n$$
 όμοιες βαθμίδες:  $\omega_{nL}=rac{\omega_0}{\sqrt{2^{1/n}-1}}.$ 

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

Με 
$$n$$
 όμοιες βαθμίδες:  $\omega_{nH}=\omega_0\sqrt{2^{1/\!n-1}}$ 

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

### Ζεύγος κοινού συλλέκτη - κοινής βάσης:

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

$$R_{\mathsf{in}} = 2r_{\pi}$$

$$egin{aligned} rac{V_o}{V_{ ext{sig}}} &= rac{1}{2} \left(rac{R_{ ext{in}}}{R_{ ext{in}} + R_{ ext{sig}}}
ight) (g_m R_L) & R_{ ext{in}} &= 2r_\pi \ f_{P1} &= rac{1}{2\pi \left(rac{C_\pi}{2} + C_\mu
ight) (R_{ ext{sig}} \parallel 2r_\pi)} & f_{P2} &= rac{1}{2\pi C_\mu R_L} \end{aligned}$$

$$f_{P2}=rac{1}{2\pi C_{\mu}R_{L}}$$

$$f_H \cong rac{1}{\sqrt{rac{1}{f_{P1}^2} + rac{1}{f_{P2}^2}}}$$

# Ζεύγος κοινής πηγής - κοινής πύλης (κασκοδική συνδεσμολογία):

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

$$A_v = -A_0^2 \frac{R_L}{R_L + A_0 r_0}$$

$$f_H \simeq rac{1}{2\pi au_H}$$

$$R_{gd1} = (1 + g_{m1}R_{d1})R_{sig} + R_{d1}$$

$$R_{qd1} = \left(1 + g_{m1}R_{d1}\right)R_{\text{sig}} + R_{d1} \qquad \qquad \tau_H = R_{\text{sig}}\left[C_{qs1} + C_{qd1}\left(1 + g_{m1}R_{d1}\right)\right] + R_{d1}\left(C_{qd1} + C_{db1} + C_{qs2}\right) + \left(R_L \parallel R_{\text{out}}\right)\left(C_L + C_{qd2}\right)$$

## Ζεύγος κοινού εκπομπού - κοινής βάσης (κασκοδική συνδεσμολογία):

$$A_{M} = -rac{r_{\pi}}{r_{\pi} + r_{\pi} + R_{
m cir}} g_{m} \left(eta r_{0} \parallel R_{L}
ight)$$

$$A_{M} = -rac{r_{\pi}}{r_{\pi} + r_{x} + R_{ ext{sig}}} g_{m} \left(eta r_{0} \parallel R_{L}
ight) \qquad \quad R_{c1} = r_{01} \parallel \left[r_{e2} \left(rac{r_{o2} + R_{L}}{r_{o2} + R_{L}/(eta_{2} + 1)}
ight)
ight]$$

$$R_{\operatorname{sig}}^{'} = r_{\pi 1} \parallel (r_{x1} + R_{\operatorname{sig}})$$

$$\tau_{H} = C_{\pi 1} R_{\pi 1} + C_{\mu 1} R_{\mu 1} + \left(C_{cs1} + C_{\pi 2}\right) R_{c1} + \left(C_{L} + C_{cs2} + C_{\mu 2}\right) \left(R_{L} \parallel R_{\text{out}}\right)$$

$$R_{\mu 1} = R_{
m sig}^{'} \left( 1 + g_{m1} R_{c1} 
ight) + R_{c1} \hspace{1.5cm} f_{H} \simeq rac{1}{2\pi au_{H}}$$

$$f_H \simeq rac{1}{2\pi au_H}$$

# Τελεστικός ενισχυτής ΜΟS δύο βαθμίδων:

$$A_v = -g_{m1} \left( r_{ds2} \parallel r_{ds4} 
ight)$$

$$g_{m1} = \sqrt{2 \mu_p C_{ox} \left(rac{W}{L}
ight)_1 I_{D1}} = \sqrt{2 \mu_p C_{ox} \left(rac{W}{L}
ight)_1 rac{I_{bias}}{2}}$$

$$R_{B} = \frac{2}{\sqrt{2\mu_{n}C_{ox}\left(W/L\right)_{12}I_{B}}}\left(\sqrt{\frac{\left(W/L\right)_{12}}{\left(W/L\right)_{13}}} - 1\right)$$

$$g_{m12} = \frac{2}{R_{B}}\left(\sqrt{\frac{\left(W/L\right)_{12}}{\left(W/L\right)_{13}}} - 1\right)$$

$$g_{mi} = g_{m12}\sqrt{\frac{I_{Di}\left(W/L\right)_{i}}{I_{B}\left(W/L\right)_{12}}}$$

$$g_{mi} = g_{m12}\sqrt{\frac{\mu_{p}I_{Di}\left(W/L\right)_{i}}{\mu_{n}I_{B}\left(W/L\right)_{12}}}$$

$$g_{m12} = rac{2}{R_B} \left( \sqrt{rac{(W/L)_{12}}{(W/L)_{13}}} - 1 
ight)$$

$$g_{mi} = g_{m12} \sqrt{rac{I_{Di}\left(W/L
ight)_i}{I_{B}\left(W/L
ight)_{12}}}$$

$$g_{mi} = g_{m12} \sqrt{rac{\mu_p I_{Di} \left( ^{W\!/\!L} 
ight)_i}{\mu_n I_B \left( ^{W\!/\!L} 
ight)_{12}}}$$

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

$$C_2 = C_{db6} + C_{db7} + C_{ad7} + C_L$$

$$\omega_Z = \frac{G_{mZ}}{C_C}$$

$$\omega_{Z} = \frac{G_{m2}}{C_{C}} \qquad \qquad \omega_{P1} = \frac{1}{C_{1}R_{1} + C_{2}R_{2} + C_{C}\left(G_{m2}R_{2}R_{1} + R_{1} + R_{2}\right)} \cong \frac{1}{R_{1}C_{C}G_{m2}R_{2}} \\ \omega_{P2} = \frac{G_{m2}C_{C}}{C_{1}C_{2} + C_{C}\left(C_{1} + C_{2}\right)} \qquad \qquad \omega_{t} = \left(G_{m1}R_{1}G_{m2}R_{2}\right)\omega_{P1} \qquad \qquad \text{Epilogy's $C_{C}$ where $\omega_{t} < \omega_{Z} < \omega_{Z} < \omega_{Z}$}$$

$$\omega_{P2} = \frac{G_{m2}C_C}{C_1C_2 + C_C(C_1 + C_2)}$$

$$\omega_t = \left(G_{m1}R_1G_{m2}R_2
ight)\omega_{P1}$$

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

$$ext{PSRR} = g_{mN} \left( r_{oP} \parallel r_{oN} 
ight)$$

$$SR \equiv \frac{dV_{\text{out}}}{dt}\Big|_{\text{max}} = \frac{I_{SS}}{C_L}$$

$$ext{GB} = A_v(0) \cdot |p_1| = (g_{m1}g_{m2}R_IR_{II}) \cdot \left(rac{1}{g_{m2}R_IR_{II}C_C}
ight) = rac{g_{m1}}{C_C}$$

$$PM = Arg[AB] = \pm 180^{\circ} - \arctan\left(\frac{\omega}{|p_1|}\right) - \arctan\left(\frac{\omega}{|p_2|}\right) - \arctan\left(\frac{\omega}{Z}\right)$$

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

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

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

## Τελεστικός ενισχυτής με είσοδο n-MOS

$$\max\left(V_{\text{in}}\right) = V_{DD} - \sqrt{\frac{I_{5}}{\beta_{3}}} - \max\left(|V_{T03}|\right) + \min\left(V_{T01}\right) \quad \min\left(V_{\text{in}}\right) = V_{SS} + \sqrt{\frac{I_{5}}{\beta_{1}}} + \max\left(V_{T01}\right) + V_{DS_{\text{sat}}} \qquad V_{DS_{\text{sat}}} = \sqrt{\frac{2I_{DS}}{\beta_{\text{sat}}}}$$

#### Τελεστικός ενισχυτής με είσοδο p-MOS

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

#### Σχεδίαση τελεστικού ενισχυτή με είσοδο n-MOS

$$\begin{split} & \text{SR} = \frac{I_5}{C_C} & A_{v1} = \frac{-g_{m1}}{g_{ds2} + g_{ds4}} = \frac{-2g_{m1}}{I_5 \cdot (\lambda_2 + \lambda_4)} & A_{v2} = \frac{-g_{m6}}{g_{ds6} + g_{ds7}} = \frac{-g_{m6}}{I_6 \cdot (\lambda_6 + \lambda_7)} \\ & \text{GB} = \frac{g_{m1}}{C_C} & p_2 = \frac{-g_{m6}}{C_L} & Z = \frac{g_{m6}}{C_C} & \beta = k' \frac{W}{L} \cong \mu_0 C_{ox} \frac{W}{L} \left( \text{A/V}^2 \right) \\ & C_C > 0.22 C_L & I_5 = \text{SR} \cdot C_C & S_3 = \left( \frac{W}{L} \right)_3 = \frac{I_5}{k_3' \left[ V_{DD} - \max \left( V_{in} \right) - \max \left( \left| V_{T03} \right| \right) + \min \left( V_{T01} \right) \right]^2} \\ & \frac{g_{m3}}{2C_{gs3}} > 10 \cdot \text{GB} & g_{m1} = \text{GB} \cdot C_C \Longrightarrow S_1 = S_2 = \frac{g_{m2}^2}{k_2' I_5} \\ & V_{DS5_{\text{sat}}} = \min \left( V_{\text{in}} \right) - V_{SS} - \sqrt{\frac{I_5}{\beta_1}} - \max \left( V_{T01} \right) \geqslant 100 \text{mV} & S_5 = \frac{2I_5}{k_5' V_{DS5_{\text{sat}}}^2} \\ & g_{m6} = 2.2 g_{m2} \left( C_L / C_C \right) & S_6 = S_4 \frac{g_{m6}}{g_{m4}} & I_6 = \frac{g_{m6}^2}{2k_6' S_6} \\ & S_6 = \frac{g_{m6}}{k_6' V_{DS6_{\text{sat}}}} & V_{DS6} = \min \left( V_{DS6} \right) = V_{DS6_{\text{sat}}} = V_{DD} - \max \left( V_{\text{out}} \right) & S_7 = S_5 \frac{I_6}{I_5} \\ & A_v = \frac{2g_{m2}g_{m6}}{I_5 \left( \lambda_2 + \lambda_4 \right) I_6 \left( \lambda_6 + \lambda_7 \right)} & P_{\text{diss}} = \left( I_5 + I_6 \right) \cdot \left( V_{DD} + |V_{SS}| \right) \end{split}$$

## Κυκλώματα ανόρθωσης

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

Ημιανορθωτής:

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

Πλήρης ανορθωτής:

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

Ημιανορθωτής με φίλτρο πυκνωτή:

$$\begin{split} V_{\mathrm{DC}} &\equiv V_o = V_p - \frac{1}{2}V_r \quad \ i_{D,\mathrm{av}} = I_L \left(1 + \pi \sqrt{^{2V_p}/\!v_r}\right) \quad \ i_{D,\mathrm{max}} = I_L \left(1 + 2\pi \sqrt{^{2V_p}/\!v_r}\right) \\ V_r &= \frac{V_p}{fCR} = \frac{I_L}{fC} \qquad \quad r = \frac{V_{\mathrm{AC,rms}}}{V_{\mathrm{DC}}} = \frac{V_r}{2\sqrt{3}V_{\mathrm{DC}}} \approx \frac{1}{2\sqrt{3}fCR} \end{split}$$

Πλήρης ανορθωτής με φίλτρο πυκνωτή:

$$\begin{split} V_r &= \frac{V_p}{2fCR} & i_{D,\text{av}} = I_L \left( 1 + \pi \sqrt{^{V_p}/_{2V_r}} \right) \quad i_{D,\text{max}} = I_L \left( 1 + 2\pi \sqrt{^{V_p}/_{2V_r}} \right) \\ r &= \frac{V_{\text{AC,rms}}}{V_{\text{DC}}} = \frac{V_r}{2\sqrt{3}V_{\text{DC}}} \approx \frac{1}{4\sqrt{3}fCR} \end{split}$$

# Κυκλώματα αναφοράς

# Πηγή Widlar:

$$V_{T} \cdot \ln \left( \frac{I_{\text{in}}}{I_{\text{out}}} \right) = I_{\text{out}} \cdot R_{2} \quad I_{\text{out}} R_{2} + \sqrt{\frac{2I_{\text{out}}}{k^{'} \left( W/L \right)_{2}}} - V_{ov1} = 0 \quad \sqrt{I_{\text{out}}} = \frac{-\sqrt{\frac{2}{k^{'} \left( W/L \right)_{2}}} - \sqrt{\frac{2}{k^{'} \left( W/L \right)_{2}}} + 4R_{2}V_{ov1}}{2R_{2}}$$

# Πηγή μεγίστου ρεύματος:

$$\begin{split} I_{\text{Out}} &= I_{\text{in}} \exp\left(-\frac{I_{\text{in}}R}{V_T}\right) & R = \frac{V_T}{I_{\text{in}}} \ln\left(\frac{I_{\text{in}}}{I_{\text{out}}}\right) & I_D = \frac{W}{L} I_t \exp\left(\frac{V_{GS} - V_t}{nV_T}\right) \cdot \left[1 - \exp\left(-\frac{V_{DS}}{V_T}\right)\right] \\ I_{\text{out}} &\simeq \frac{W}{L} I_t \exp\left(\frac{V_{GS2} - V_t}{nV_T}\right) \simeq I_{\text{in}} \exp\left(-\frac{I_{\text{in}R}}{nV_T}\right) & I_{\text{out}} = \frac{k^{'}}{2} \left(\frac{W}{L}\right)_2 V_{ov2}^2 = \frac{k^{'}}{2} \left(\frac{W}{L}\right)_2 (V_{ov1} - I_{\text{in}}R)^2 \\ S_{V_{\text{sup}}}^{I_{\text{out}}} &= \frac{V_{\text{sup}}}{I_{\text{out}}} \cdot \frac{\partial I_{\text{out}}}{\partial V_{\text{sup}}} & S_{V_{\text{sup}}}^{I_{\text{out}}} = \left(\frac{1}{1 + \frac{I_{\text{out}}R_2}{V_T}}\right) \cdot \frac{V_{CC}}{I_{\text{in}}} \cdot \frac{\partial I_{\text{in}}}{\partial V_{CC}} = \left(\frac{1}{1 + \frac{I_{\text{out}}R_2}{V_T}}\right) S_{V_{CC}}^{I_{\text{in}}} \end{split}$$

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