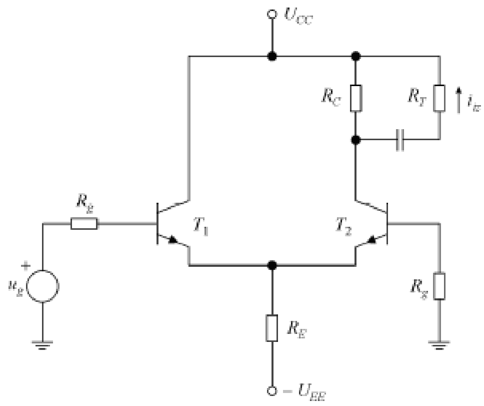
1. DIFERENCIJSKO POJAČALO – BIPOLARNI TRANZISTORI

1. zadatak

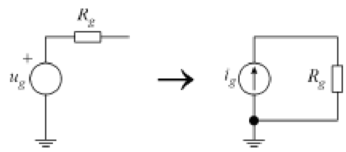


$$I_{BQ1}=I_{BQ2}=\frac{U_{EE}-U_{BEQ1}}{R_g+2(1+\beta)R_E}=27{,}9{,}1\ \mu\text{A},\quad I_{CQ1}=I_{CQ2}=\beta I_{BQ1}=2{,}79\ \text{mA}\,,$$

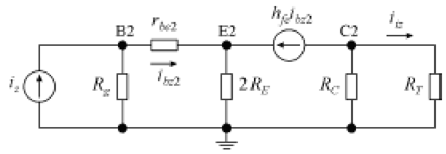
$$U_{CEQ1}\approx U_{CC}+U_{EE}-2R_E I_{CQ1}=12{,}8\ \text{V}\,,$$

$$U_{CEQ2}\approx U_{CC}+U_{EE}-(R_C+2R_E)I_{CQ1}=10{,}1\ \text{V}\,,$$

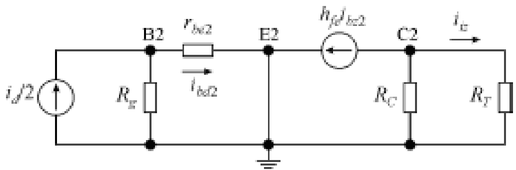
$$r_{be1}=r_{be1}=\frac{U_T}{I_{BQ1}}=896\ \Omega\,.$$



$$I_{gm}=\frac{U_{gm}}{R_g}=40\ \mu\text{A}\,.$$



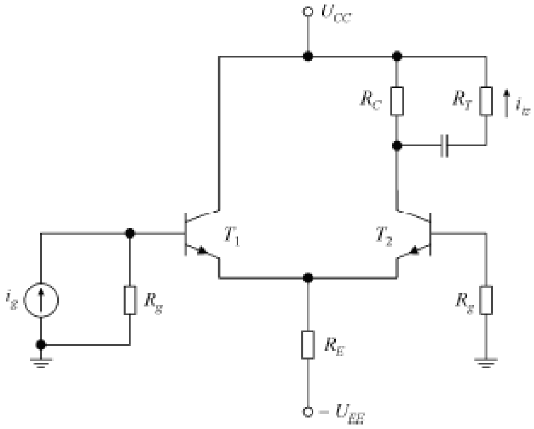
$$A_{Iz}=\frac{i_{iz}}{i_z}=-h_{fe}\frac{R_C}{R_C+R_T}\frac{R_g}{R_g+r_{be2}+2(1+h_{fe})R_E}=-0{,}112\,.$$



$$A_{Id}=\frac{i_{iz}}{i_d}=\frac{1}{2}\frac{i_{iz}}{i_d/2}=-\frac{h_{fe}}{2}\frac{R_C}{R_C+R_T}\frac{R_g}{R_g+r_{be2}}=-16{,}3\,,$$

$$I_{izm}=A_{Iz}I_{zm}+A_{Id}I_{dm}=650\ \mu\text{A},\quad i_{iz}=650\sin\omega t\ \mu\text{A}\,.$$

1. zadatak

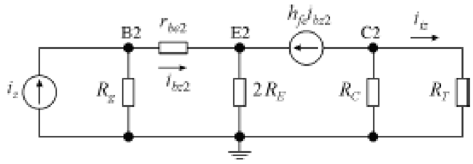


$$I_{BQ1} = I_{BQ2} = \frac{U_{EE} - U_{BEQ1}}{R_g + 2(1+\beta) R_E} = 14\ \mu\text{A}, \quad I_{CQ1} = I_{CQ2} = \beta I_{BQ1} = 1{,}4\ \text{mA},$$

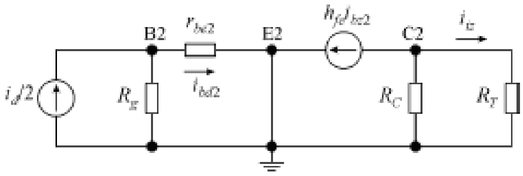
$$U_{CEQ1} \approx U_{CC} + U_{EE} - 2 R_E I_{CQ1} = 12{,}8\ \text{V},$$

$$U_{CEQ2} \approx U_{CC} + U_{EE} - (R_C + 2 R_E) I_{CQ1} = 12{,}2\ \text{V},$$

$$r_{be1} = r_{be1} = \frac{U_T}{I_{BQ1}} = 1{,}79\ \text{k}\Omega .$$



$$A_{Iz} = \frac{i_{iz}}{i_z} = -h_{fe} \frac{R_C}{R_C + R_T} \frac{R_g}{R_g + r_{be2} + 2(1+h_{fe}) R_E} = -0{,}099 .$$



$$A_{Id} = \frac{i_{iz}}{i_d} = \frac{1}{2} \frac{i_{iz}}{i_d/2} = -\frac{h_{fe}}{2} \frac{R_C}{R_C + R_T} \frac{R_g}{R_g + r_{be2}} = -14{,}3 ,$$

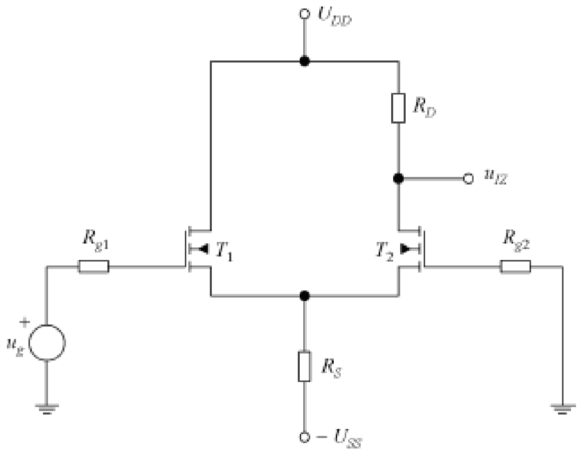
$$\rho = \frac{|A_{Id}|}{|A_{Iz}|} = \frac{14{,}3}{0{,}099} = 144 ,$$

$$I_{zm} = \frac{I_{gm}}{2} = 5\ \mu\text{A}, \quad I_{dm} = -I_{gm} = -10\ \mu\text{A},$$

$$I_{izm} = A_{Iz} I_{zm} + A_{Id} I_{dm} = 143\ \mu\text{A}, \quad i_{iz} = 143 \sin \omega t\ \mu\text{A} .$$

2. DIFERENCIJSKO POJAČALO – UNIPOLARNI TRANZISTORI

1. zadatak



$$I_{DQ1} = \frac{U_{SS} - U_{GSQ1}}{2R_S} = \frac{K}{2}\left(U_{GSQ1} - U_{GS0}\right)^2,$$

$$12 \cdot U_{GSQ1}^2 - 47 \cdot U_{GSQ1} + 33 = 0 \quad \rightarrow \quad U_{GSQ1} = 3\ \text{V} = U_{GSQ2},$$

$$I_{DQ1} = I_{DQ2} = \frac{U_{SS} - U_{GSQ1}}{2R_S} = 1\ \text{mA},$$

$$U_{DSQ1} = U_{DD} + U_{SS} - 2R_S I_{DQ1} = 18\ \text{V}, \quad U_{DSQ2} = U_{DD} + U_{SS} - \left(R_D + 2R_S\right) I_{DQ2} = 15\ \text{V},$$

$$g_{m2} == K\left(U_{GSQ2} - U_{GS0}\right) = 2\ \text{mA/V}, \quad r_{d2} \rightarrow \infty$$

$$A_{Vz} = \frac{u_{iz}}{u_z} = \frac{-g_{m2} R_D}{1 + 2g_{m2} R_S} = -0{,}24, \quad A_{Vd} = \frac{u_{iz}}{u_d} = \frac{-g_{m2} R_D}{2} = -3,$$

$$\rho = \frac{\left|A_{Vd}\right|}{\left|A_{Vz}\right|} = 12{,}5,$$

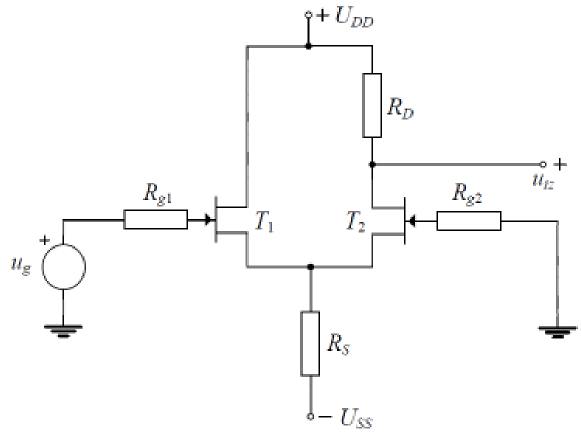
$$U_{zm} = \frac{U_{gm} + 0}{2} = 100\ \text{mV}, \quad U_{dm} = 0 - U_{gm} = -200\ \text{mV},$$

$$U_{izm} = A_{Vz} U_{zm} + A_{Vd} U_{dm} = 576\ \text{mV}, \quad u_{iz} = 576 \sin \omega t\ \text{mV}.$$

3. DIFERENCIJSKA POJAČALA S JFETOM

1. zadatak – 5 bodova

Za diferencijsko pojačalo na slici zadano je $U_{DD}=U_{SS}=12V$, $R_{g1}=R_{g2}=1k\Omega$, $R_D=3k\Omega$, $R_S=5k\Omega$. Tranzistori T_1 i T_2 imaju jednake parametre $I_{DSS}=6mA$ i $U_P=-6V$. Zanemariti porast struja odvoda u području zasićenja.



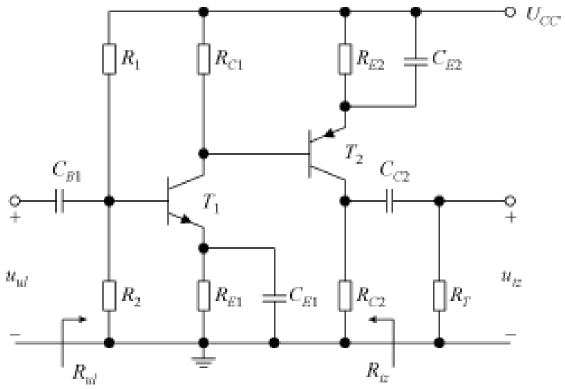
a) Izračunati statičku radnu točku. (2 boda)

b) Izračunati naponsko pojačanje zajedničkog i diferencijskog signala $A_{Vz}=u_{iz}/u_z$ i $A_{Vd}=u_{iz}/u_d$ te faktor potiskivanja ρ. (2 boda)

c) Izračunati izlazni napon ako je napon $u_g=100\sin(\omega t)$ mV. (1 bod)

4. KASKADNA POJAČALA

2. zadatak



$$U_{BB1} = \frac{R_2}{R_1 + R_2} U_{CC} = 2{,}4\ \text{V}, \quad R_{B1} = R_1 \| R_2 = 20\ \text{k}\Omega,$$

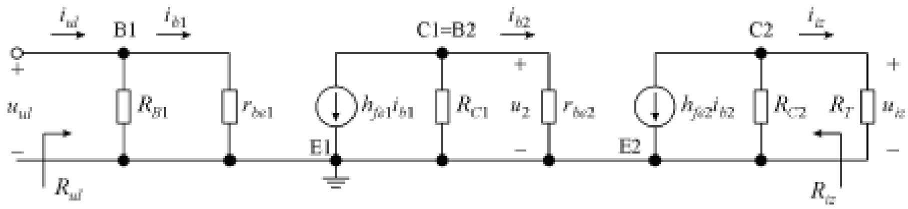
$$I_{BQ1} = \frac{U_{BB1} - U_{BEQ1}}{R_{B1} + (1+\beta) R_{E1}} = 14\ \mu\text{A}, \quad I_{CQ1} = \beta I_{BQ1} = 1{,}4\ \text{mA},$$

$$(I_{CQ1} + I_{BQ2}) R_{C1} = -(1+\beta) I_{BQ2} R_{E2} - U_{BEQ2},$$

$$I_{BQ2} = -\frac{I_{CQ1} R_{C1} + U_{BEQ2}}{R_{C1} + (1+\beta) R_{E2}} = -19\ \mu\text{A}, \quad I_{CQ2} = \beta I_{BQ2} = -1{,}9\ \text{mA},$$

$$U_{CEQ1} \approx U_{CC} - (R_{C1} + R_{E1}) I_{CQ1} = 5\ \text{V}, \quad U_{CEQ2} \approx -U_{CC} - (R_{E2} + R_{C2}) I_{CQ2} = -3{,}5\ \text{V},$$

$$r_{be1} = \frac{U_T}{I_{BQ1}} = 1{,}78\ \text{k}\Omega, \quad r_{be2} = \frac{U_T}{-I_{BQ2}} = 1{,}32\ \text{k}\Omega.$$



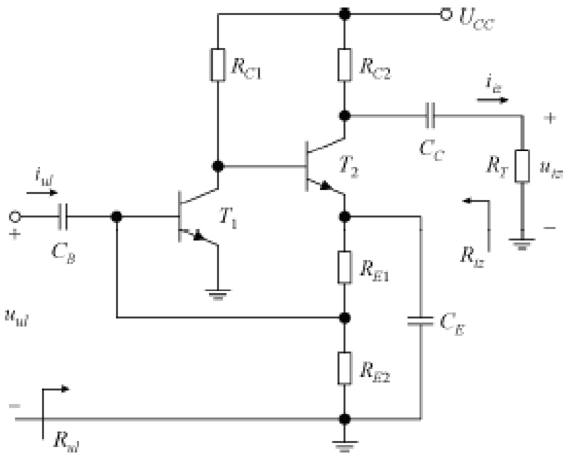
$$A_{V2} = \frac{u_{iz}}{u_2} = -h_{fe} \frac{R_{C2} \| R_T}{r_{be2}} = -75{,}8, \quad A_{V1} = \frac{u_2}{u_{ul}} = -h_{fe} \frac{R_{C1} \| r_{be2}}{r_{be1}} = -55{,}8,$$

$$A_V = \frac{u_{iz}}{u_{ul}} = A_{V2} A_{V1} = 4230,$$

$$R_{ul} = \frac{u_{ul}}{i_{ul}} = R_{B1} \| r_{be1} = 1{,}63\ \text{k}\Omega, \quad A_I = \frac{i_{iz}}{i_{ul}} = \frac{u_{iz} / R_T}{u_{ul} / R_{ul}} = A_V \frac{R_{ul}}{R_T} = -3450,$$

$$R_{iz} = R_{C2} = 2\ \text{k}\Omega.$$

2. zadatak

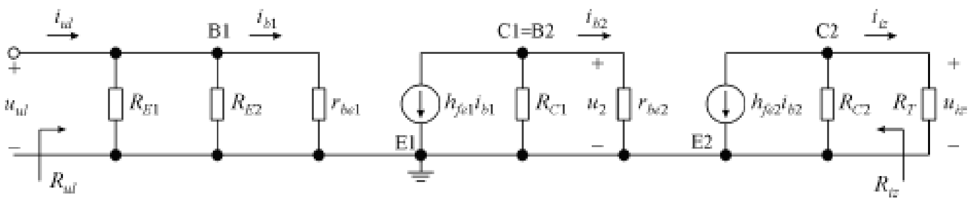


$$I_{CQ2} \approx \frac{U_{BEQ1}}{R_{E2}} = 2{,}5 \text{ mA},$$

$$U_{CC} \approx I_{CQ1} R_{C1} + U_{BEQ2} + I_{CQ2}\left(R_{E1} + R_{E2}\right) \;\rightarrow\; I_{CQ1} = 2{,}03 \text{ mA},$$

$$U_{CEQ1} \approx U_{CC} - I_{CQ1} R_{C1} = 3{,}9 \text{ V}, \; U_{CEQ2} \approx U_{CC} - I_{CQ2}\left(R_{C2} + R_{E1} + R_{E2}\right) = 3{,}8 \text{ V},$$

$$r_{be1} = \frac{U_T}{I_{BQ1}} = \frac{\beta U_T}{I_{CQ1}} = 1{,}23 \text{ k}\Omega, \; r_{be2} = \frac{U_T}{I_{BQ2}} = \frac{\beta U_T}{I_{CQ2}} = 1 \text{ k}\Omega,$$



$$A_{V2} = \frac{u_{iz}}{u_2} = -h_{fe}\frac{R_{C2} \| R_T}{r_{be2}} = -40, \; A_{V1} = \frac{u_2}{u_{ul}} = -h_{fe} h_{fe}\frac{R_{C1} \| r_{be2}}{r_{be1}} = -65,$$

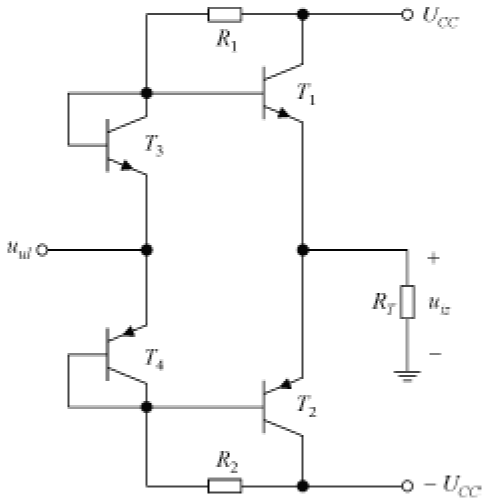
$$A_V = \frac{u_{iz}}{u_{ul}} = A_{V2} A_{V1} = 2600,$$

$$R_{ul} = \frac{u_{ul}}{i_{ul}} = R_{E1} \| R_{E2} \| r_{be1} = 186 \;\Omega, \; A_I = \frac{i_{iz}}{i_{ul}} = \frac{u_{iz} / R_T}{u_{ul} / R_{ul}} = A_V \frac{R_{ul}}{R_T} = 967,$$

$$R_{iz} = R_{C2} = 2 \text{ k}\Omega.$$

5. POJAČALA SNAGE

3. zadatak



$$\text{Bez signala} \quad \rightarrow \quad P_{T1}\big|_{I_{cm}=0} = P_{T1,\min} = U_{CC}\, I_{CQ1} \quad \rightarrow \quad I_{CQ1} = \frac{P_{T1,\min}}{U_{CC}} = 23 \text{ mA},$$

$$\text{Uz signal} \quad \rightarrow \quad P_{T1} = U_{CC} I_{CQ1} + U_{CC}\frac{I_{cm}}{\pi} - R_T \frac{I_{cm}^2}{4},$$

$$\frac{\partial P_{T1}}{\partial I_{cm}} = \frac{U_{CC}}{\pi} - R_T \frac{I_{cm}}{2} \equiv 0 \quad \rightarrow \quad I_{cm}\big|_{P_{T1\max}} = \frac{2}{\pi}\frac{U_{CC}}{R_T},$$

$$P_{T1,\max} = U_{CC}\, I_{CQ1} + \frac{U_{CC}^2}{\pi^2 R_T} = P_{T1,\min} + \frac{U_{CC}^2}{\pi^2 R_T} \quad \rightarrow \quad R_T = \frac{U_{CC}^2}{\pi^2\left(P_{T1,\max} - P_{T1,\min}\right)} = 8\ \Omega,$$

$$I_{RQ1} = \frac{U_{CC} - U_{BEQ1}}{R_1} = I_{BQ3} + I_{CQ3} + I_{BQ1} = \frac{2+\beta}{\beta} I_{CQ1},$$

$$R_1 = R_2 = \frac{U_{CC} - U_\gamma}{(2+\beta)I_{CQ1}}\beta = 390\ \Omega,$$

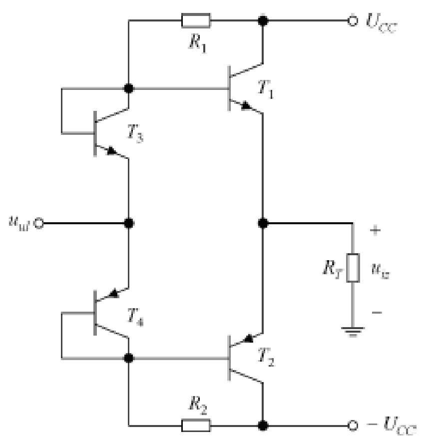
$$P_{T3} = U_{CEQ3}\, I_{CQ3} = U_{BEQ3}\, I_{CQ3} = 16 \text{ mW},$$

$$U_{CC} = R_1\, I_{B\max} + u_{BE} + (1+\beta) R_T\, I_{B\max},$$

$$U_{iz m\max} = (1+\beta) R_T\, I_{B\max} = \left(U_{CC} - U_\gamma\right)\frac{(1+\beta)R_T}{R_1 + (1+\beta)R_T} = 5{,}8 \text{ V},$$

$$P_{RT\max} = \frac{U_{iz m\max}^2}{2R_T} = \frac{5{,}8^2}{2\cdot 8} = 2{,}1 \text{ W}.$$

3. zadatak



$$P_{RT} = \frac{U_{izm}^2}{2R_T} \quad \rightarrow \quad U_{izm} = 8\ \text{V},$$

$$U_{izm} = \left(U_{CC} - U_{BE}\right)\frac{(1+\beta)R_T}{R_1 + (1+\beta)R_T} \quad \rightarrow \quad R_1 = 267\ \Omega = R_2,$$

$$I_{RQ1} = \frac{U_{CC} - U_{BEQ}}{R_1} = 42\ \text{mA},$$

$$I_{RQ1} = I_{BQ3} + I_{CQ3} + I_{BQ1} = \frac{2+\beta}{\beta} I_{CQ3} \quad \rightarrow \quad I_{CQ3} = 41\ \text{mA} = I_{CQ1},$$

$$P_{T3} = U_{BEQ}\left(I_{BQ3} + I_{CQ3}\right) = 29\ \text{mW},$$

$$P_{T1} = U_{CC} I_{CQ1} + \frac{P_{CC} - P_{RT}}{2} = U_{CC} I_{CQ1} + U_{CC}\frac{I_{cm}}{\pi} - R_T \frac{I_{cm}^2}{4},$$

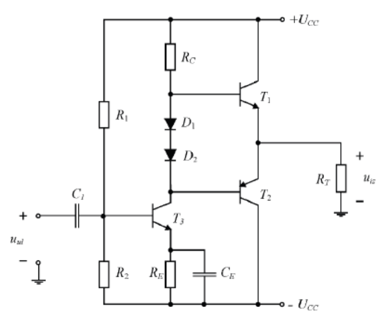
$$\text{za } I_{cm} = 0 \quad \rightarrow \quad P_{T1} = P_{T1\min} = U_{CC} I_{CQ1} = 0{,}49\ \text{W},$$

$$\frac{\partial P_{T1}}{\partial I_{cm}} = \frac{U_{CC}}{\pi} - R_T \frac{I_{cm}}{2} \equiv 0 \quad \rightarrow \quad I_{cm}\big|_{P_{T1\max}} = \frac{2}{\pi}\frac{U_{CC}}{R_T},$$

$$\text{za } I_{cm} = \frac{2}{\pi}\frac{U_{CC}}{R_T} \quad \rightarrow \quad P_{T1} = P_{T1\max} = U_{CC} I_{CQ1} + \frac{U_{CC}^2}{\pi^2 R_T} = 2{,}32\ \text{W}.$$

3. zadatak – 5 bodova

Za pojačalo sa slike zadano je: U_{CC}=12V, R_C=130Ω, R_g= 50Ω i R_T= 4Ω. Parametri svih tranzistora su jednaki ß=80, U_γ=0.7V i $|U_{CEzas}|$=0.2V. Pretpostaviti da je $I_{DQ} \approx |I_{BQ} + I_{CQ}|$, te da je na frekvenciji signala impedancija kondenzatora C_E zanemarivo mala. Izračunati:



a) statičku struju I_{CQ3} tranzistora T_3 (1 bod),

b) maksimalnu moguću amplitudu za pozitivnu poluperiodu izlaznog napona (1 bod),

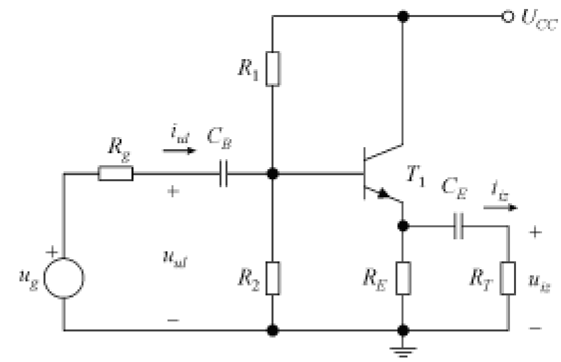
c) maksimalnu moguću amplitudu za negativnu poluperiodu izlaznog napona (1 bod),

d) maksimalnu srednju snagu trošila (1 bod),

e) statičke snage na otporima R_C i R_E (1 bod).

6. NISKOFREKVENCIJSKA ANALIZA

4. zadatak

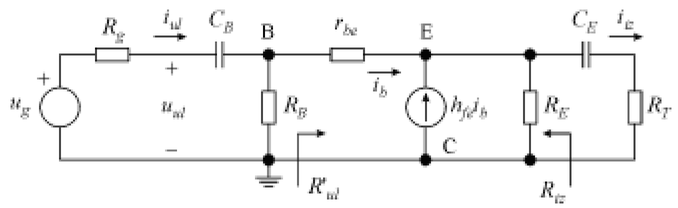


$$U_{BB} = \frac{R_2}{R_1 + R_2} U_{CC} = 7,5 \text{ V}, \; R_B = R_1 \| R_2 = 75 \text{ k}\Omega,$$

$$I_{BQ} = \frac{U_{BB} - U_{BEQ}}{R_B + (1+\beta) R_E} = 12,8 \; \mu\text{A}, \; I_{CQ} = \beta I_{BQ} = 1,28 \text{ mA},$$

$$U_{CEQ} \approx U_{CC} - R_E I_{CQ} = 6,24 \text{ V},$$

$$r_{be} = \frac{U_T}{I_{BQ}} = 1,95 \text{ k}\Omega,$$



$$\frac{U_{iz}}{U_{ul}} = \frac{(1+h_{fe})(R_E \| R_T)}{r_{be} + (1+h_{fe})(R_E \| R_T)} = 0,959, \; R'_{ul} = r_{be} + (1+h_{fe})(R_E \| R_T) = 47,4 \text{ k}\Omega,$$

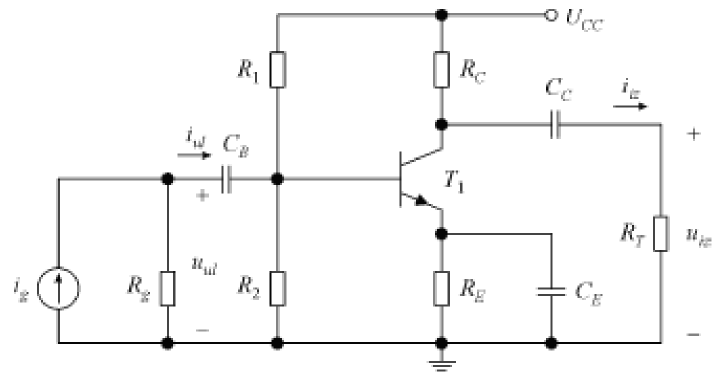
$$\frac{U_{ul}}{U_g} = \frac{R_B \| R'_{ul}}{R_g + R_B \| R'_{ul}} = 0,983, \; A_{Vg0} = \frac{U_{iz}}{U_g} = \frac{U_{iz}}{U_{ul}} \frac{U_{ul}}{U_g} = 0,943,$$

$$\tau_B = (R_g + R_B \| R'_{ul}) C_B = 29,5 \text{ ms}, \; \omega_B = \frac{1}{\tau_B} = 33,9 \text{ rad/s},$$

$$\tau_E = \left(\frac{r_{be} + R_g \| R_B}{1 + h_{fe}} \Bigg\| R_E + R_T \right) C_E = 2,62 \text{ ms}, \; \omega_E = \frac{1}{\tau_E} = 382 \text{ rad/s},$$

$$\omega_d = \omega_E = 382 \text{ rad/s}, \; f_d = \frac{\omega_d}{2\pi} = 60,8 \text{ Hz}.$$

3. zadatak

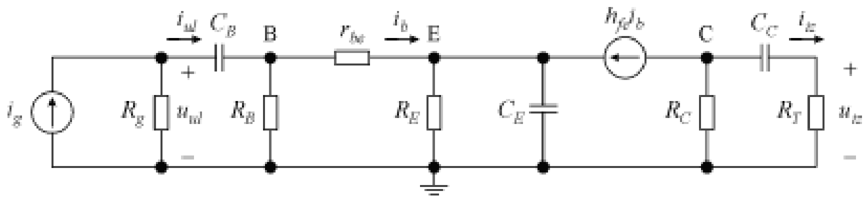


$$U_{BB} = \frac{R_2}{R_1 + R_2} U_{CC} = 1{,}36\ \text{V}\ ,\ R_B = R_1 \| R_2 = 18{,}2\ \text{k}\Omega\ ,$$

$$I_{BQ} = \frac{U_{BB} - U_{BEQ}}{R_B + (1+\beta) R_E} = 3\ \mu\text{A}\ ,\ \ I_{CQ} = \beta I_{BQ} = 0{,}3\ \text{mA}\ ,$$

$$U_{CEQ} \approx U_{CC} - (R_C + R_E) I_{CQ} = 11{,}7\ \text{V}\ ,$$

$$r_{be} = \frac{U_T}{I_{BQ}} = 8{,}33\ \text{k}\Omega\ ,$$



$$A_{Ig0} = \frac{I_{iz}}{I_g} = \frac{I_{iz}}{I_b}\frac{I_b}{I_g} = -h_{fe} \frac{R_C}{R_C + R_T} \frac{R_g \| R_B}{R_g \| R_B + r_{be}} = -55{,}4\ ,$$

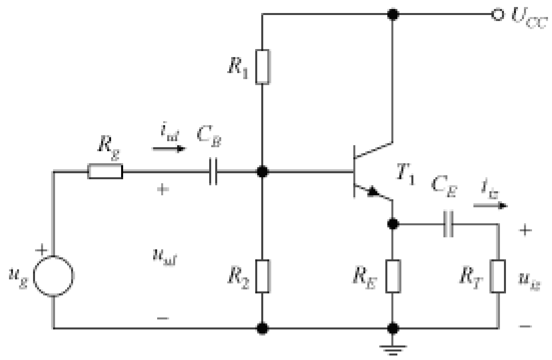
$$\tau_B = \left(R_g + R_B \| r_{be}\right) C_B = 167\ \text{ms}\ ,\ \ \omega_B = \frac{1}{\tau_B} = 5{,}99\ \text{rad/s}\ ,$$

$$\tau_E = \left(\frac{r_{be} + R_g \| R_B}{1 + h_{fe}} \Bigg\| R_E \right) C_E = 9{,}69\ \text{ms}\ ,\ \ \omega_E = \frac{1}{\tau_E} = 103\ \text{rad/s}\ ,$$

$$\tau_C = (R_C + R_T) C_C = 150\ \text{ms}\ ,\ \ \omega_C = \frac{1}{\tau_C} = 6{,}67\ \text{rad/s}\ ,$$

$$\omega_d = \omega_E = 103\ \text{rad/s}\ ,\ f_d = \frac{\omega_d}{2\pi} = 16{,}4\ \text{Hz}\ .$$

4. zadatak

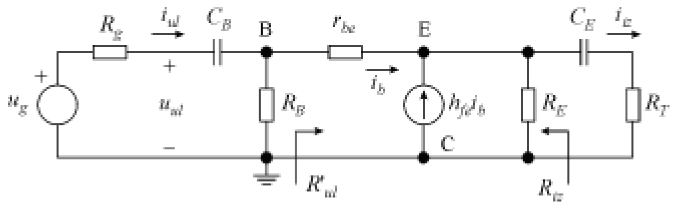


$$U_{BB} = \frac{R_2}{R_1 + R_2} U_{CC} = 8 \text{ V},\ R_B = R_1 \| R_2 = 100 \text{ k}\Omega,$$

$$I_{BQ} = \frac{U_{BB} - U_{BEQ}}{R_B + (1+\beta) R_E} = 14{,}5\ \mu\text{A},\ I_{CQ} = \beta I_{BQ} = 1{,}45 \text{ mA},$$

$$U_{CEQ} \approx U_{CC} - R_E I_{CQ} = 6{,}2 \text{ V},$$

$$r_{be} = \frac{U_T}{I_{BQ}} = 1{,}72 \text{ k}\Omega,$$



$$\frac{U_{iz}}{U_{ul}} = \frac{(1+h_{fe})(R_E \| R_T)}{r_{be} + (1+h_{fe})(R_E \| R_T)} = 0{,}979,\ R'_{ul} = r_{be} + (1+h_{fe})(R_E \| R_T) = 82{,}5 \text{ k}\Omega,$$

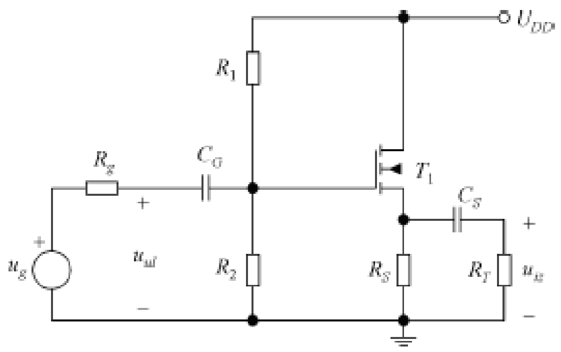
$$\frac{U_{ul}}{U_g} = \frac{R_B \| R'_{ul}}{R_g + R_B \| R'_{ul}} = 0{,}989,\ A_{vg0} = \frac{U_{iz}}{U_g} = \frac{U_{iz}}{U_{ul}} \frac{U_{ul}}{U_g} = 0{,}968,$$

$$\tau_B = \left(R_g + R_B \| R'_{ul}\right) C_B = 22{,}9 \text{ ms},\ \omega_B = \frac{1}{\tau_B} = 43{,}7 \text{ rad/s},$$

$$\tau_E = \left(\frac{r_{be} + R_g \| R_B}{1 + h_{fe}} \middle\| R_E + R_T \right) C_E = 5{,}11 \text{ ms},\ \omega_E = \frac{1}{\tau_E} = 196 \text{ rad/s},$$

$$\omega_d = \omega_E = 196 \text{ rad/s},\ f_d = \frac{\omega_d}{2\pi} = 31{,}2 \text{ Hz}.$$

4. zadatak



$$U_{GG} = \frac{R_2}{R_1 + R_2} U_{DD} = 8 \text{ V}, \quad R_G = R_1 \| R_2 = 2 \text{ M}\Omega,$$

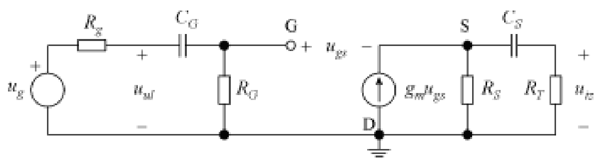
$$U_{GG} = U_{GSQ} + R_S I_{DQ} = U_{GSQ} + R_S \frac{K}{2} (U_{GSQ} - U_{GS0})^2,$$

$$U_{GSQ}^2 + \left(\frac{2}{R_S K} - 2U_{GS0} \right) U_{GSQ} + U_{GS0}^2 - \frac{2U_{GG}}{R_S K} = 0 \quad \rightarrow \quad U_{GSQ}^2 - 1{,}2 \cdot U_{GSQ} + 5{,}4 = 0,$$

$$U_{GSQ} = 0{,}6 + 2{,}4 = 3 \text{ V},$$

$$I_{DQ} = \frac{U_{GG} - U_{GSQ}}{R_S} = 5 \text{ mA}, \quad U_{DSQ} = U_{DD} - R_S I_{DQ} = 7 \text{ V},$$

$$g_m = K \left(U_{GSQ} - U_{GS0} \right) = 5 \text{ mA/V}.$$



$$\frac{U_{iz}}{U_{gs}} = g_m \left(R_S \| R_T \right), \quad U_{gs} = U_{ul} - U_{iz},$$

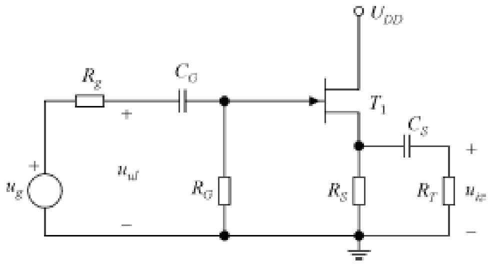
$$A_{Vg0} = \frac{U_{iz}}{U_g} = \frac{U_{iz}}{U_{gs}} \frac{U_{gs}}{U_{ul}} \frac{U_{ul}}{U_g} = \frac{g_m \left(R_S \| R_T \right)}{1 + g_m \left(R_S \| R_T \right)} \frac{R_G}{R_g + R_G} = 0{,}714,$$

$$\tau_G = \left(R_g + R_G \right) C_G = 40 \text{ ms}, \quad \omega_G = \frac{1}{\tau_G} = 25 \text{ rad/s},$$

$$\tau_S = \left(R_S \| \frac{1}{g_m} + R_T \right) C_S = 5{,}8 \text{ ms}, \quad \omega_S = \frac{1}{\tau_S} = 172 \text{ rad/s},$$

$$\omega_d = \omega_S = 172 \text{ rad/s}, \quad f_d = \frac{\omega_d}{2\pi} = 27{,}4 \text{ Hz}.$$

2. zadatak



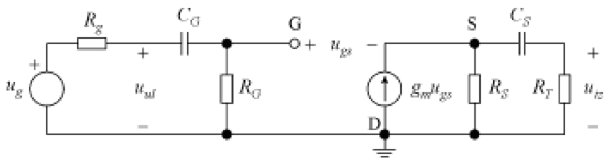
$$U_{GSQ} + I_{DQ} R_S = 0 \quad \rightarrow \quad I_{DQ} = I_{DSS}\left(1 - \frac{U_{GSQ}}{U_P}\right)^2 = -\frac{U_{GSQ}}{R_S},$$

$$U_{GSQ}^2 + \left(\frac{U_P^2}{R_S I_{DSS}} - 2U_P\right)U_{GSQ} + U_P^2 = 0,$$

$$U_{GSQ}^2 + 15U_{GSQ} + 36 = 0 \quad \rightarrow \quad U_{GSQ} = -7{,}5 + \sqrt{7{,}5^2 - 36} = -3\ \text{V},$$

$$I_{DQ} = -\frac{U_{GSQ}}{R_S} = 3\ \text{mA}, \quad U_{DSQ} = U_{DD} - R_S I_{DQ} = 9\ \text{V},$$

$$g_m = -\frac{2 I_{DSS}}{U_P}\left(1 - \frac{U_{GSQ}}{U_P}\right) = 2\ \text{mA/V}.$$



$$\frac{U_{iz}}{U_{gs}} = g_m\left(R_S \| R_T\right), \quad U_{gs} = U_{ul} - U_{iz},$$

$$A_{Vg0} = \frac{U_{iz}}{U_g} = \frac{U_{iz}}{U_{gs}}\frac{U_{gs}}{U_{ul}}\frac{U_{ul}}{U_g} = \frac{g_m\left(R_S \| R_T\right)}{1 + g_m\left(R_S \| R_T\right)}\frac{R_G}{R_g + R_G} = 0{,}615,$$

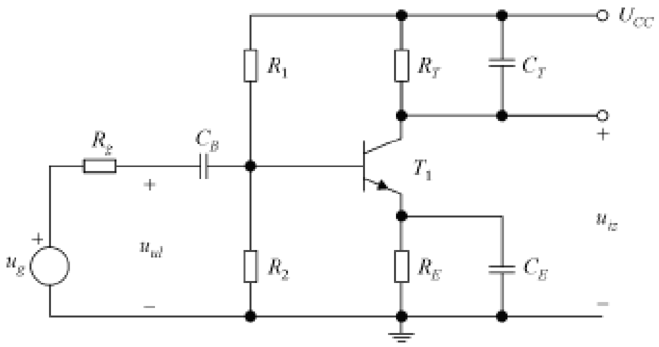
$$\tau_G = \left(R_g + R_G\right)C_G = 40\ \text{ms}, \quad \omega_G = \frac{1}{\tau_G} = 25\ \text{rad/s},$$

$$\tau_S = \left(R_S \| \frac{1}{g_m} + R_T\right)C_S = 8{,}67\ \text{ms}, \quad \omega_S = \frac{1}{\tau_S} = 115\ \text{rad/s},$$

$$\omega_d = \omega_S = 115\ \text{rad/s}, \quad f_d = \frac{\omega_d}{2\pi} = 18{,}3\ \text{Hz}.$$

7. VISOKOFREKVENCIJSKA ANALIZA

1. zadatak

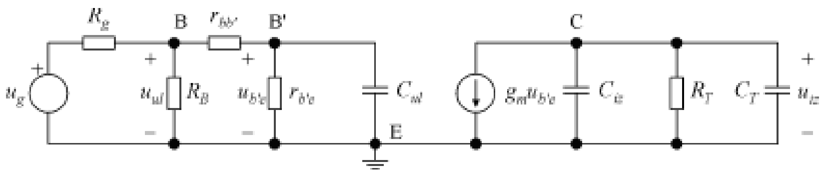


$$U_{BB} = \frac{R_2}{R_1 + R_2} U_{CC} = 3\ \text{V}, \quad U_{BB} = \frac{R_2}{R_1 + R_2} U_{CC} = 3\ \text{V},$$

$$I_{BQ} = \frac{U_{BB} - U_{BEQ}}{R_B + (1+\beta) R_E} = 17{,}6\ \mu\text{A}, \quad I_{CQ} = \beta I_{BQ} = 1{,}76\ \text{mA},$$

$$U_{CEQ} \approx U_{CC} - (R_T + R_E) I_{CQ} = 10{,}6\ \text{V},$$

$$r_{b'e} = \frac{U_T}{I_{BQ}} = 1{,}42\ \text{k}\Omega, \quad g_m = \frac{I_{CQ}}{U_T} = 70{,}4\ \text{mA/V}.$$



$$A_{Vg0} = \frac{U_{iz}}{U_g} = \frac{U_{iz}}{U_{b'e}} \frac{U_{b'e}}{U_{ul}} \frac{U_{ul}}{U_g} = -g_m R_T \frac{r_{b'e}}{r_{bb'} + r_{b'e}} \frac{R_B \| (r_{bb'} + r_{b'e})}{R_g + R_B \| (r_{bb'} + r_{b'e})} = -80{,}3,$$

$$K = \frac{U_{iz}}{U_{b'e}} = -g_m R_T = -141,$$

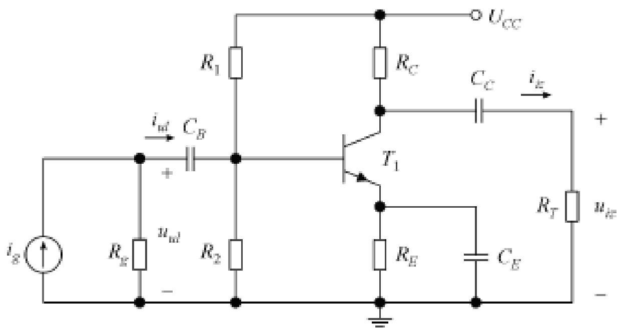
$$C_{ul} = C_{b'e} + C_{b'c}(1-K) = 324\ \text{pF}, \quad C_{iz} = C_{b'c} \frac{K-1}{K} = 2\ \text{pF},$$

$$\tau_{ul} = \left[\left(R_g \| R_B + r_{bb'} \right) \| r_{b'e} \right] C_{ul} = 194\ \text{ns}, \quad \tau_{iz} = R_T (C_{iz} + C_T) = 34\ \text{ns},$$

$$\omega_{ul} = \frac{1}{\tau_{ul}} = 5{,}15 \cdot 10^6\ \text{rad/s}, \quad \omega_{iz} = \frac{1}{\tau_{iz}} = 29{,}4 \cdot 10^6\ \text{rad/s},$$

$$\omega_g = \omega_{ul} = 5{,}15 \cdot 10^6\ \text{rad/s}, \quad f_g = \frac{\omega_g}{2\pi} = 820\ \text{kHz}.$$

1. zadatak

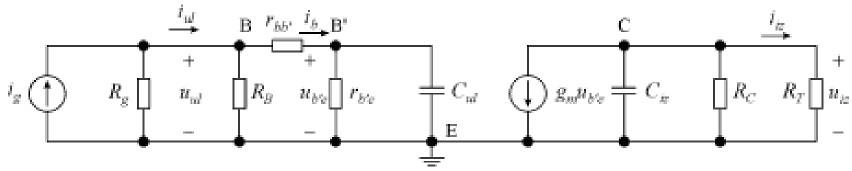


$$U_{BB} = \frac{R_2}{R_1 + R_2} U_{CC} = 3 \text{ V}, \quad R_B = R_1 \| R_2 = 37{,}5 \text{ k}\Omega ,$$

$$I_{BQ} = \frac{U_{BB} - U_{BEQ}}{R_B + (1+\beta) R_E} = 9{,}6 \ \mu\text{A}, \quad I_{CQ} = \beta I_{BQ} = 0{,}96 \text{ mA} ,$$

$$U_{CEQ} \approx U_{CC} - (R_C + R_E) I_{CQ} = 6{,}24 \text{ V} ,$$

$$r_{b'e} = \frac{U_T}{I_{BQ}} = 2{,}60 \text{ k}\Omega, \quad g_m = \frac{I_{CQ}}{U_T} = 38{,}4 \text{ mA/V} .$$



$$A_{Ig0} = \frac{I_{iz}}{I_g} = \frac{I_{iz}}{U_{b'e}} \frac{U_{b'e}}{I_b} \frac{I_b}{I_g} = -g_m \frac{R_C}{R_C + R_T} \frac{r_{b'e}(R_g \| R_B)}{(R_g \| R_B) + r_{bb'} + r_{b'e}} = -59{,}8 ,$$

$$K = \frac{U_{iz}}{U_{b'e}} = -g_m R_T = -30{,}7 ,$$

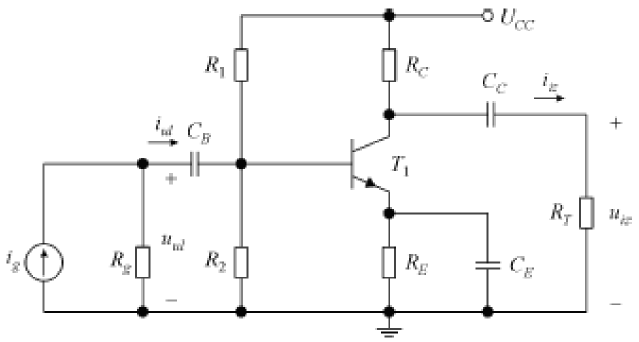
$$C_{ul} = C_{b'e} + C_{b'c}(1 - K) = 88{,}4 \text{ pF}, \quad C_{iz} = C_{b'c} \frac{K-1}{K} = 2{,}06 \text{ pF} ,$$

$$\tau_{ul} = \left[(R_g \| R_B + r_{bb'}) \| r_{b'e} \right] C_{ul} = 173 \text{ ns}, \quad \tau_{iz} = (R_C \| R_T) C_{iz} = 1{,}65 \text{ ns} ,$$

$$\omega_{ul} = \frac{1}{\tau_{ul}} = 5{,}78 \cdot 10^6 \text{ rad/s}, \quad \omega_{iz} = \frac{1}{\tau_{iz}} = 606 \cdot 10^6 \text{ rad/s} ,$$

$$\omega_g = \omega_{ul} = 5{,}78 \cdot 10^6 \text{ rad/s}, \quad f_g = \frac{\omega_g}{2\pi} = 0{,}92 \text{ MHz} .$$

3. zadatak

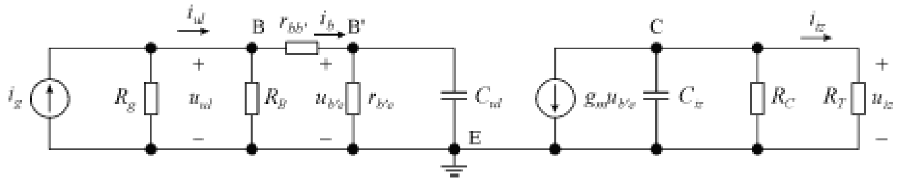


$$U_{BB} = \frac{R_2}{R_1 + R_2} U_{CC} = 2{,}4 \text{ V}, \quad R_B = R_1 \| R_2 = 80 \text{ k}\Omega ,$$

$$I_{BQ} = \frac{U_{BB} - U_{BEQ}}{R_B + (1+\beta) R_E} = 13 \ \mu\text{A}, \quad I_{CQ} = \beta I_{BQ} = 1{,}3 \text{ mA} ,$$

$$U_{CEQ} \approx U_{CC} - (R_C + R_E) I_{CQ} = 7{,}45 \text{ V} ,$$

$$r_{b'e} = \frac{U_T}{I_{BQ}} = 1{,}92 \text{ k}\Omega, \quad g_m = \frac{I_{CQ}}{U_T} = 52 \text{ mA/V} .$$



$$A_{Ig0} = \frac{I_{iz}}{I_g} = \frac{I_{iz}}{U_{b'e}} \frac{U_{b'e}}{I_b} \frac{I_b}{I_g} = -g_m \frac{R_C}{R_C + R_T} \frac{r_{b'e}(R_g \| R_B)}{(R_g \| R_B) + r_{bb'} + r_{b'e}} = -52{,}8 ,$$

$$K = \frac{U_{iz}}{U_{b'e}} = -g_m (R_C \| R_T) = -39 ,$$

$$C_{ul} = C_{b'e} + C_{b'c}(1-K) = 100 \text{ pF} , \quad C_{iz} = C_{b'c} \frac{K-1}{K} = 2{,}05 \text{ pF} ,$$

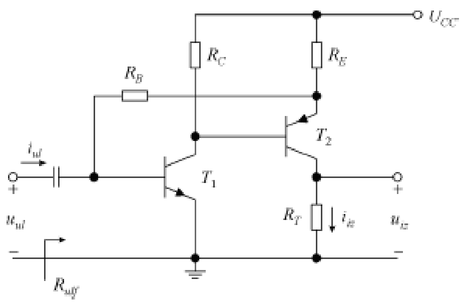
$$\tau_{ul} = \left[\left(R_g \| R_B + r_{bb'} \right) \| r_{b'e} \right] C_{ul} = 137 \text{ ns} , \quad \omega_{ul} = \frac{1}{\tau_{ul}} = 7{,}3 \cdot 10^6 \text{ rad/s} ,$$

$$\tau_{iz} = (R_C \| R_T) C_{iz} = 1{,}54 \text{ ns}, \quad \omega_{iz} = \frac{1}{\tau_{iz}} = 650 \cdot 10^6 \text{ rad/s} ,$$

$$\omega_g = \omega_{ul} = 7{,}3 \cdot 10^6 \text{ rad/s}, \quad f_g = \frac{\omega_g}{2\pi} = 1{,}16 \text{ MHz} .$$

8. POJAČALA S POVRATNOM VEZOM

2. zadatak



$$U_{CC} \approx \beta_2 I_{BQ1} R_C + U_{BEQ2} + I_{BQ1} R_B + U_{BEQ1}, \quad U_{BEQ1} \approx -U_{BEQ2},$$

$$I_{BQ1} \approx \frac{U_{CC}}{\beta_1 R_C + R_B} = 25\ \mu\text{A},$$

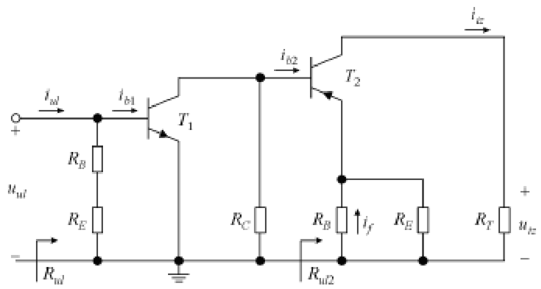
$$\beta_1 I_{BQ1} R_C \approx -\beta_2 I_{BQ2} R_E - U_{BEQ2}, \quad -I_{BQ2} \approx \frac{\beta_1 I_{BQ1} R_C + U_{BEQ2}}{\beta_2 R_E} = 39\ \mu\text{A},$$

$$I_{CQ1} = \beta_1 I_{BQ1} = 2{,}5\ \text{mA}, \quad -I_{CQ2} = -\beta_2 I_{BQ2} = 3{,}9\ \text{mA},$$

$$U_{CEQ1} \approx U_{CC} - R_C I_{CQ1} = 2{,}5\ \text{V}, \quad -U_{CEQ2} \approx U_{CC} + (R_E + R_T) I_{CQ2} = 2{,}5\ \text{V},$$

$$r_{be1} = \frac{U_T}{I_{BQ1}} 1\ \text{k}\Omega, \quad r_{be2} = \frac{U_T}{-I_{BQ2}} = 640\ \Omega.$$

Povratna veza – strujna-paralelna



$$A_{I2} = \frac{i_{iz}}{i_{b2}} = -h_{fe2} = -100, \quad R_{ul2} = r_{be2} + (1 + h_{fe2})(R_B \| R_E) = 295\ \text{k}\Omega,$$

$$A_{I1} = \frac{i_{b2}}{i_{ul}} = \frac{i_{b2}}{i_{b1}} \frac{i_{b1}}{i_{ul}} = -h_{fe1} \frac{R_C}{R_C + R_{ul2}} \frac{R_B + R_E}{R_B + R_E + r_{be1}} = -1{,}65,$$

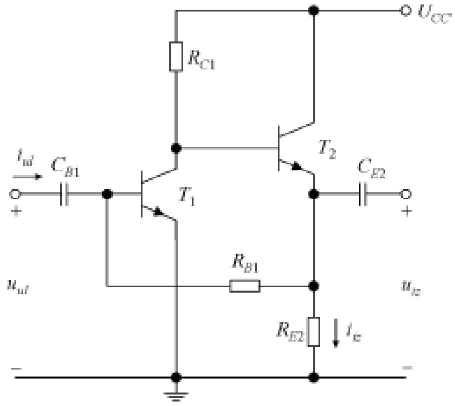
$$A_I = \frac{i_{iz}}{i_{ul}} = \frac{i_{iz}}{i_{b2}} \frac{i_{b2}}{i_{ul}} = A_{I2} A_{I1} = 165, \quad \beta = \frac{i_f}{i_{iz}} \approx \frac{R_E}{R_B + R_E} = \frac{1}{34{,}3}.$$

$$R_{ul} = (R_B + R_E) \| r_{be1} = 990\ \Omega,$$

$$A_{If} = \frac{A_I}{1 + \beta A_I} = 28{,}4, \quad R_{ulf} = \frac{R_{ul}}{1 + \beta A_I} = 170\ \Omega,$$

$$A_{Vf} = \frac{u_{iz}}{u_{ul}} = \frac{i_{iz} R_T}{i_{ul} R_{ulf}} = A_{If} \frac{R_T}{R_{ulf}} = 33{,}4.$$

2. zadatak



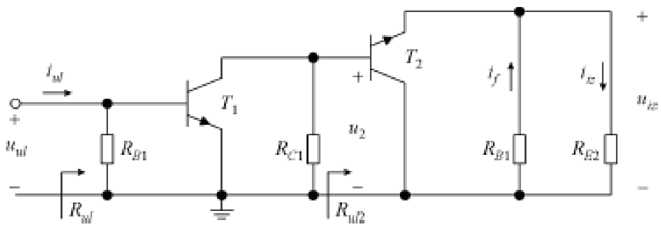
$$U_{CC} \approx \beta I_{BQ1} R_{C1} + U_{BEQ2} + I_{BQ1} R_{B1} + U_{BEQ1} \quad \rightarrow \quad I_{BQ1} \approx \frac{U_{CC} - 2U_{BEQ}}{\beta R_{C1} + R_{B1}} = 21{,}2\ \mu\text{A},$$

$$\left[(1+\beta) I_{BQ2} - I_{BQ1}\right] R_{E2} = I_{BQ1} R_{B1} + U_{BEQ1} \ \rightarrow\ I_{BQ2} = \frac{U_{BEQ} + I_{BQ1}(R_{B1} + R_{E2})}{(1+\beta) R_{E2}} = 14{,}2\ \mu\text{A},$$

$$I_{CQ1} = \beta I_{BQ1} = 2{,}12\ \text{mA}, \quad I_{CQ2} = \beta I_{BQ2} = 1{,}42\ \text{mA},$$

$$r_{be1} = \frac{U_T}{I_{BQ1}} 1{,}18\ \text{k}\Omega, \quad r_{be2} = \frac{U_T}{I_{BQ2}} = 1{,}76\ \text{k}\Omega.$$

Povratna veza – naponska-paralelna



$$A_{V2} = \frac{u_{iz}}{u_{ul}} = \frac{(1+h_{fe})(R_{B1} \| R_{E2})}{r_{be2} + (1+h_{fe})(R_{B1} \| R_{E2})} = 0{,}991,$$

$$R_{ul2} = r_{be2} + (1+h_{fe})(R_{B1} \| R_{E2}) = 200\ \text{k}\Omega,$$

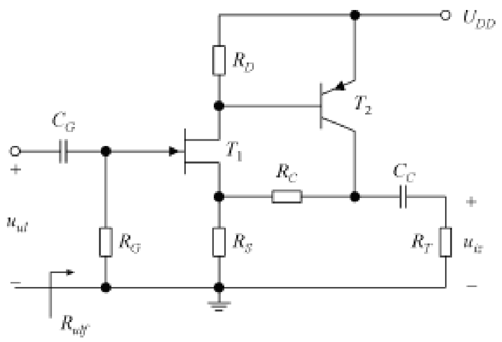
$$A_{V1} = \frac{u_2}{u_{ul}} = -h_{fe} \frac{R_{C1} \| R_{ul2}}{r_{be1}} = -332, \quad R_{ul} = R_{B1} \| r_{be1} = 1{,}17\ \text{k}\Omega,$$

$$R_M = A_{V2} A_{V1} R_{ul} = -385\ \text{V/mA}, \quad \beta = \frac{i_f}{u_{iz}} = -\frac{1}{R_{B1}} = -\frac{1}{100}\ \text{mA/V},$$

$$R_{Mf} = \frac{R_M}{1+\beta R_M} = -79{,}4\ \text{V/mA}, \quad R_{ulf} = \frac{R_{ul}}{1+\beta R_M} = 243\ \Omega,$$

$$A_{Vf} = \frac{u_{iz}}{u_{ul}} = \frac{u_{iz}}{i_{ul} R_{ulf}} = \frac{R_{Mf}}{R_{ulf}} = -327, \quad A_{If} = \frac{i_{iz}}{i_{ul}} = \frac{u_{iz}/R_{E2}}{i_{ul}} = \frac{R_{Mf}}{R_{E2}} = -39{,}7.$$

4. zadatak



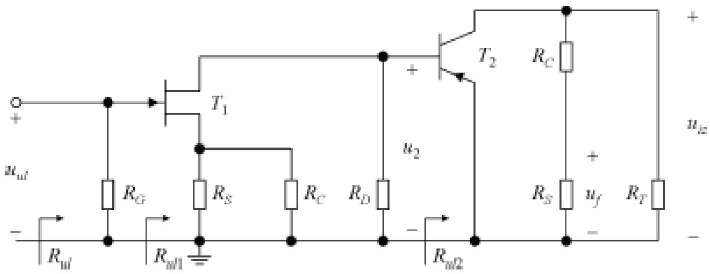
$$I_{DQ}R_D = -U_{BEQ} \quad \rightarrow \quad I_{DQ} = -\frac{U_{BEQ}}{R_D} = \frac{U_{\gamma}}{R_D} = 1\ \text{mA}\,,$$

$$I_{DQ} = I_{DSS}\left(1-\frac{U_{GSQ}}{U_P}\right)^2 \quad \rightarrow \quad U_{GSQ} = U_P\left(1-\sqrt{\frac{I_{DQ}}{I_{DSS}}}\right) = -1{,}5\ \text{V}\,,$$

$$U_{GSQ} + \left(I_{DQ} - I_{CQ}\right)R_S = 0 \quad \rightarrow \quad I_{CQ} = \frac{U_{GSQ}}{R_S} + I_{DQ} = -2\ \text{mA}\,,$$

$$g_m = -\frac{2I_{DSS}}{U_P}\left(1-\frac{U_{GSQ}}{U_P}\right) = 4\ \text{mA/V}\,, \quad r_{be} = \frac{U_T}{-I_{BQ2}} = \frac{\beta U_T}{-I_{CQ2}} = 1{,}25\ \text{k}\Omega\,.$$

Povratna veza – naponska-serijska



$$A_{V2} = \frac{u_{iz}}{u_2} = -h_{fe}\frac{\left(R_C + R_S\right)\|R_T}{r_{be}} = -230\,, \quad R_{ul2} = r_{be} = 1{,}25\ \Omega\,,$$

$$A_{V1} = \frac{u_2}{u_{ul}} = \frac{-g_m\left(R_D\|R_{ul2}\right)}{1+g_m\left(R_S\|R_C\right)} = -0{,}637\,, \quad R_{ul1} = \infty\,,$$

$$A_V = \frac{u_{iz}}{u_{ul}} = \frac{u_{iz}}{u_2}\frac{u_2}{u_{ul}} = A_{V2}A_{V1} = 147\,, \quad \beta = \frac{u_f}{u_{iz}} = \frac{R_S}{R_C + R_S} = \frac{1}{11}\,,$$

$$A_{Vf} = \frac{A_V}{1+\beta A_V} = 10{,}2\,,$$

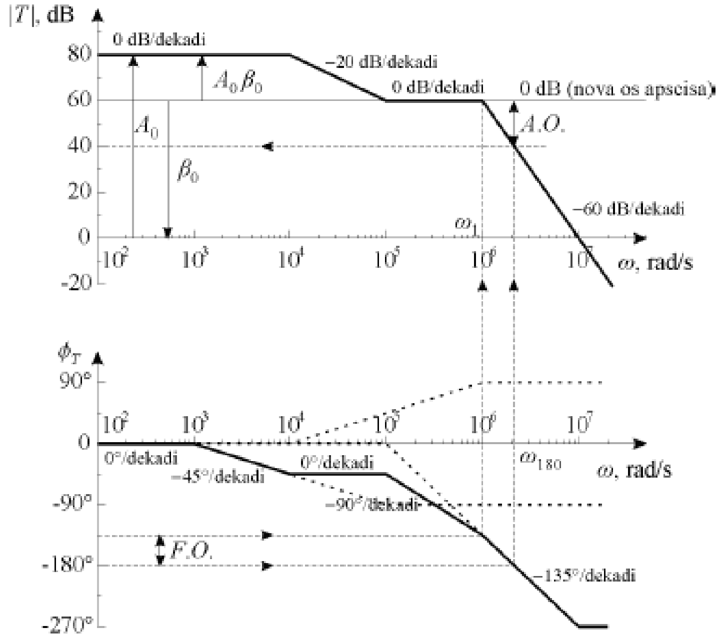
$$R_{ul1f} = R_{ul1}\left(1+\beta A_V\right) = \infty\,, \quad R_{ulf} = R_G\|R_{ul1f} = R_G = 1\ \text{M}\Omega\,.$$

9. STABILNOST POVRATNE VEZE

3. zadatak

$$A(j\omega) = \frac{-10^4\left(1 + j\omega/10^5\right)}{\left(1 + j\omega/10^4\right)\left(1 + j\omega/10^6\right)^2}\ , \qquad \beta(j\omega) = \frac{\beta_0}{1 + j\omega/10^6}\ .$$

$$\text{Uz } \beta_0 = -1 \quad \rightarrow \quad T(j\omega) = \beta(j\omega)A(j\omega) = \frac{10^4\left(1 + j\omega/10^5\right)}{\left(1 + j\omega/10^4\right)\left(1 + j\omega/10^6\right)^3}\ .$$



$$\phi_T(j\omega_1) = F.O. - 180° = -135° \quad \rightarrow \quad \left|T(j\omega_1)\right| = \left|\beta(j\omega_1)A(j\omega_1)\right| = 1 = 0 \text{ dB}\,,$$

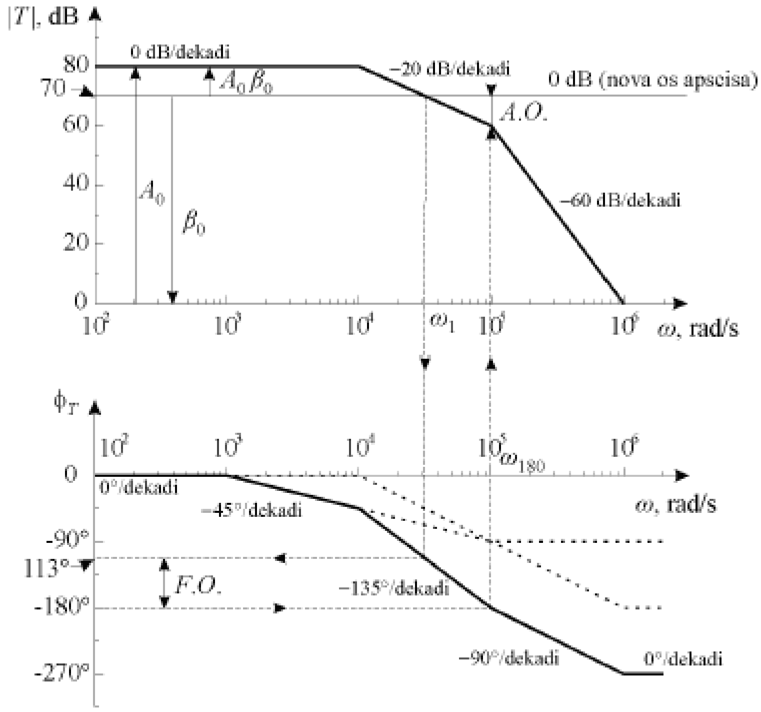
$$\beta_0 = -\,0{,}001\,,$$

$$\phi_T(j\omega_{180}) = -180° \quad \rightarrow \quad \left|T(j\omega_{180})\right| = -\,20 \text{ dB} = A.O.$$

3. zadatak

$$A(j\omega)=\frac{-10^{18}}{\left(10^4+j\omega\right)\left(10^5+j\omega\right)^2} \ .$$

$$\text{Uz } \beta=-1 \quad\rightarrow\quad T(j\omega)=\beta A(j\omega)=\frac{10^4}{\left(1+j\omega/10^4\right)\left(1+j\omega/10^5\right)^2} \ .$$



$$\phi_T(j\omega_{180})=-180° \quad\rightarrow\quad \left|T(j\omega_{180})\right|=A.O.=-10 \text{ dB},$$

$$20\log\left|\beta\right|=20\log\left|\beta A_0\right|-20\log\left|A_0\right|=10-80=-70 \text{ dB},$$

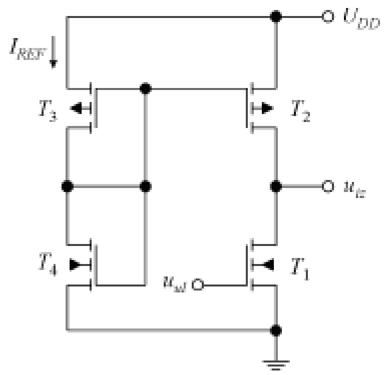
$$\beta=-3{,}16\cdot 10^{-4},$$

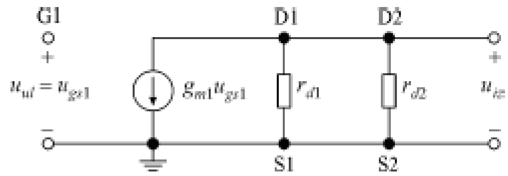
$$\left|T(j\omega_1)\right|=\left|\beta(j\omega_1)A(j\omega_1)\right|=1=0 \text{ dB} \quad\rightarrow\quad \phi_T(j\omega_1)=-112{,}5°,$$

$$F.O.=\phi_T(j\omega_1)+180°=67{,}5°$$

10. INTEGRIRANI ANALOGNI SKLOPOVI

4. zadatak





$$I_{DQ1} = -I_{DQ2} = -I_{DQ3} = I_{REF}, \quad g_{m1} = \sqrt{2K_n'(W_1/L_1)I_{DQ1}} = \sqrt{2K_n'(W_1/L_1)I_{REF}},$$

$$r_{d1} = \frac{1}{\lambda_n I_{DQ1}} = \frac{1}{\lambda_n I_{REF}}, \quad r_{d2} = \frac{1}{\lambda_p I_{DQ2}} = \frac{1}{-\lambda_p I_{REF}},$$

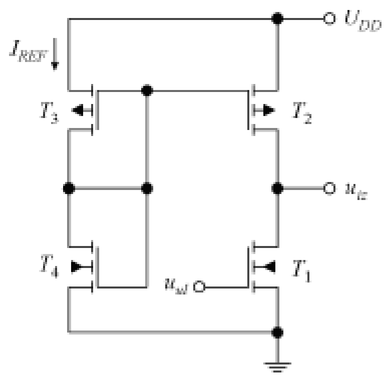
$$A_V = \frac{u_{iz}}{u_{ul}} = \frac{u_{iz}}{u_{gs1}} = -g_{m1}\left(r_{d1} \| r_{d2}\right) = -\frac{g_{m1}}{1/r_{d1} + 1/r_{d2}} = -\frac{\sqrt{2K_n'(W_1/L_1)}}{\lambda_1 - \lambda_2}\frac{1}{\sqrt{I_{REF}}}.$$

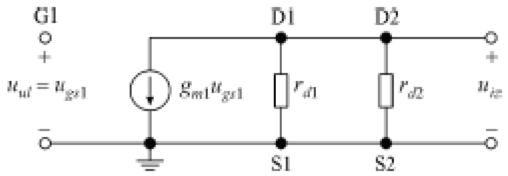
$$I_{REF} = \frac{2K_n'(W_1/L_1)}{A_V^2\left(\lambda_n - \lambda_p\right)^2} = 29{,}6\ \mu\text{A},$$

$$U_{GSQ3} = -\sqrt{\frac{-2I_{REF}}{K_p'(W_3/L_3)}} + U_{GS0p} = -0{,}92\ \text{V}, \quad U_{GSQ4} = U_{DD} + U_{GSQ3} = 2{,}58\ \text{V},$$

$$\frac{W_4}{L_4} = \frac{2I_{DQ4}}{K_n'\left(U_{GS4} - U_{GS0n}\right)^2} = 0{,}056.$$

4. zadatak





$$I_{DQ1} = -I_{DQ2} = -I_{DQ3} = I_{REF}, \quad g_{m1} = \sqrt{2K_n'(W_1/L_1)I_{DQ1}} = \sqrt{2K_n'(W_1/L_1)I_{REF}},$$

$$r_{d1} = \frac{1}{\lambda_n I_{DQ1}} = \frac{1}{\lambda_n I_{REF}}, \quad r_{d2} = \frac{1}{\lambda_p I_{DQ2}} = \frac{1}{-\lambda_p I_{REF}},$$

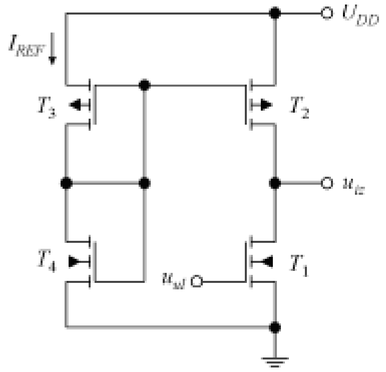
$$A_V = \frac{u_{iz}}{u_{ul}} = \frac{u_{iz}}{u_{gs1}} = -g_{m1}\left(r_{d1} \| r_{d2}\right) = -\frac{g_{m1}}{1/r_{d1} + 1/r_{d2}} = -\frac{\sqrt{2K_n'(W_1/L_1)}}{\lambda_1 - \lambda_2}\frac{1}{\sqrt{I_{REF}}}.$$

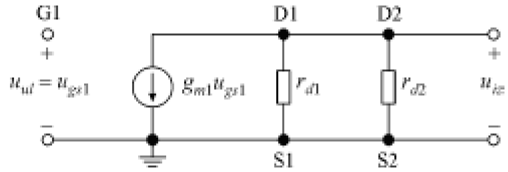
$$I_{REF} = \frac{2K_n'(W_1/L_1)}{A_V^2\left(\lambda_n - \lambda_p\right)^2} = 71\ \mu\text{A},$$

$$U_{GSQ3} = -\sqrt{\frac{-2I_{REF}}{K_p'(W_3/L_3)}} + U_{GS0p} = -1{,}04\ \text{V}, \quad U_{GSQ4} = U_{DD} + U_{GSQ3} = 2{,}26\ \text{V},$$

$$\frac{W_4}{L_4} = \frac{2I_{DQ4}}{K_n'\left(U_{GS4} - U_{GS0n}\right)^2} = 0{,}215.$$

4. zadatak





$$I_{DQ1} = -I_{DQ2} = -I_{DQ3} = I_{REF}, \quad g_{m1} = \sqrt{2K_n'(W_1/L_1)I_{DQ1}} = \sqrt{2K_n'(W_1/L_1)I_{REF}},$$

$$r_{d1} = \frac{1}{\lambda_n I_{DQ1}} = \frac{1}{\lambda_n I_{REF}}, \quad r_{d2} = \frac{1}{\lambda_p I_{DQ2}} = \frac{1}{-\lambda_p I_{REF}},$$

$$A_V = \frac{u_{iz}}{u_{ul}} = \frac{u_{iz}}{u_{gs1}} = -g_{m1}(r_{d1} \| r_{d2}) = -\frac{g_{m1}}{1/r_{d1} + 1/r_{d2}} = -\frac{\sqrt{2K_n'(W_1/L_1)}}{\lambda_1 - \lambda_2} \frac{1}{\sqrt{I_{REF}}}.$$

$$I_{REF} = \frac{2K_n'(W_1/L_1)}{A_V^2(\lambda_n - \lambda_p)^2} = 34{,}1\ \mu\text{A},$$

$$U_{GSQ3} = -\sqrt{\frac{-2I_{REF}}{K_p'(W_3/L_3)}} + U_{GS0p} = -0{,}97\ \text{V}, \quad U_{GSQ4} = U_{DD} + U_{GSQ3} = 2{,}53\ \text{V},$$

$$\frac{W_4}{L_4} = \frac{2I_{DQ4}}{K_n'(U_{GS4} - U_{GS0n})^2} = 0{,}085.$$