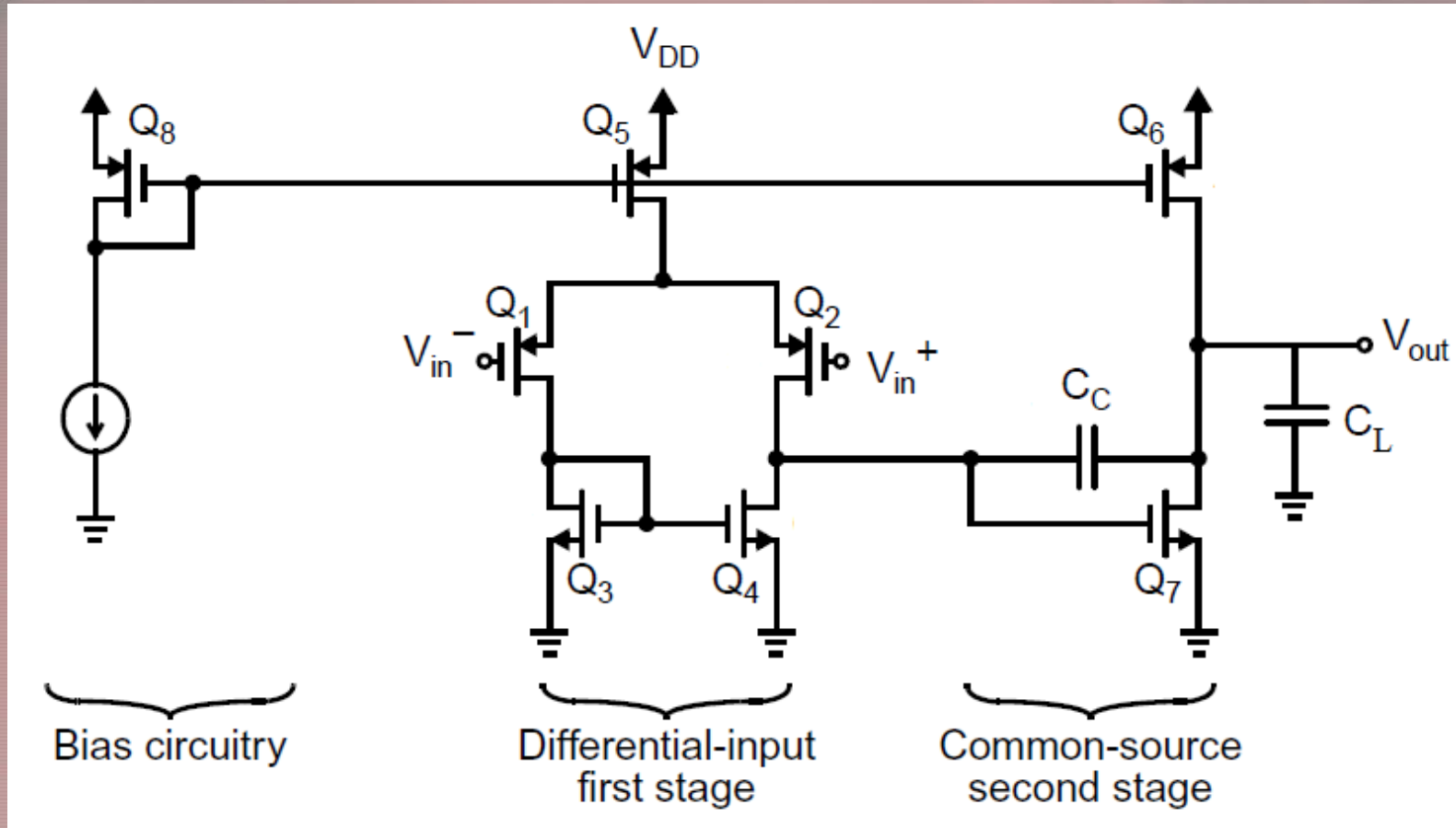


Postupak projektovanja dvostepenog operacionog pojačavača

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Dvostepeni operacioni pojačavač



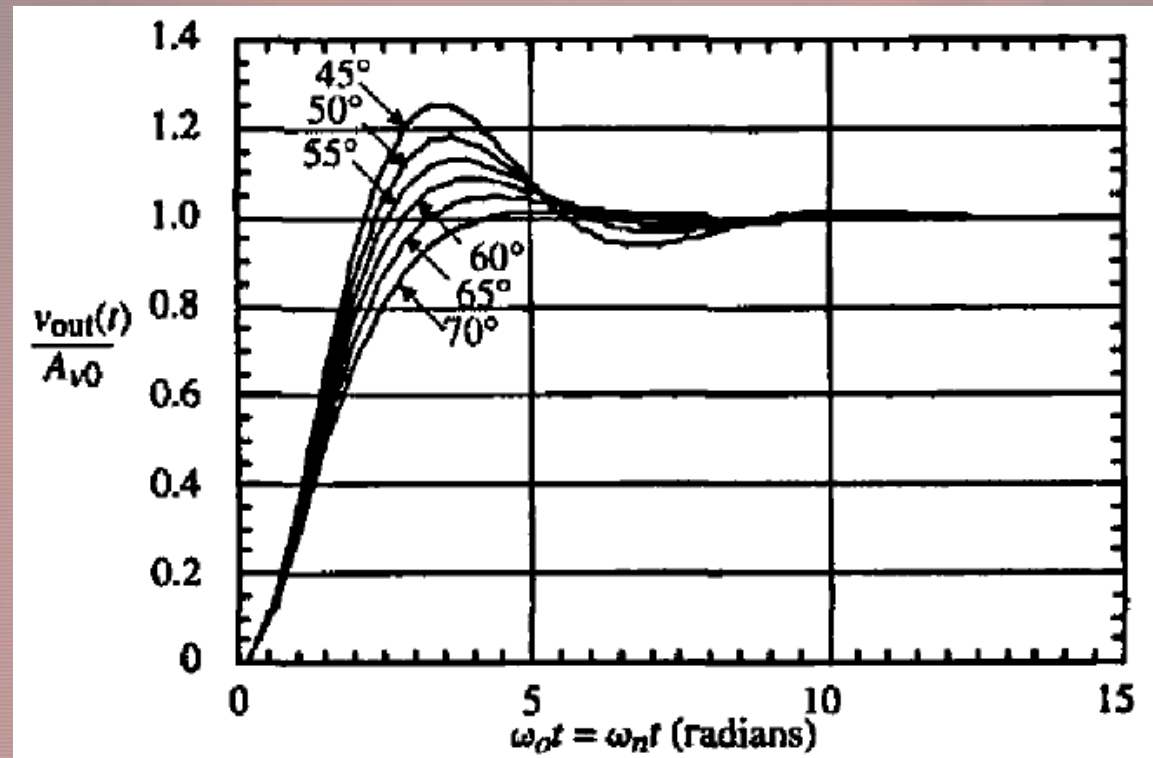
Specifikacije

- $A_{V0_dB} \geq 60 \text{ dB}$
- $GBW \geq 10 \text{ MHz}$
- $CMIR \sim (0,2 \text{ V} - 2,0 \text{ V})$
- $C_L = 10 \text{ pF}$
- $SR = 10 \text{ V}/\mu\text{s}$
- $OR \sim (0,2 \text{ V} - 1 \text{ V})$
- $P_{diss} \leq 1,5 \text{ mW}$
- $PM \geq 60^\circ$
- $V_{DD} = 3,3 \text{ V} , V_{SS} = 0 \text{ V}$
- $V_{os} \leq \pm 10 \text{ mV}$

Opterećenje integrisanih kola

- Ulazne kapacitivnosti tranzistora u 0,35 μm AMS tehnologiji
 - $W/L = 10\mu\text{m}/0,35\mu\text{m} \rightarrow C_g \approx 18 \text{ fF}$
 - $W/L = 100\mu\text{m}/3,5\mu\text{m} \rightarrow C_g \approx 1,62 \text{ pF}$
- Osciloskop
 - $R \approx 1 \text{ M}\Omega$, $C \approx 10 - 15 \text{ pF}$
 - Sonde sa slabljenjem od 10x
- Standardno DIP (eng. *Dual-Inline Package*) keramičko kućište
 - 1 – 4 pF po čvoru povezanom na pinu
- Standardni koaksijalni kabel
 - Približno 100 pF/m

Fazna margina



Odziv sistema II reda pri različitim vrednostima fazne margine

Fazna margina

Table 5.1 The relationship between PM, ω_t/ω_{eq} , Q factor, and percentage overshoot

| PM (Phase margin) | ω_t/ω_{eq} | Q factor | Percentage overshoot for a step input |
|----------------------|------------------------|----------|---------------------------------------|
| 55° | 0.700 | 0.925 | 13.3% |
| 60° | 0.580 | 0.817 | 8.7% |
| 65° | 0.470 | 0.717 | 4.7% |
| 70° | 0.360 | 0.622 | 1.4% |
| 75° | 0.270 | 0.527 | 0.008% |

$$\frac{1}{\omega_{eq}} \cong \sum_{i=2}^m \frac{1}{\omega_{pi}} - \sum_{i=1}^n \frac{1}{\omega_{zi}}$$

- U praksi ω_{eq} se određuje iz simulacija kao frekvencija na kojoj prenosna funkcija ima fazni pomeraj od -135° (-90° ω_{p1} , -45° ω_{eq})
- ω_t , frekvencija jediničnog pojačanja povratne petlje ($A(s)\beta$), $\omega_t = \beta(A_0\omega_{p1}) \rightarrow \omega_t/\omega_{p1} = A_0\beta \gg 1 \rightarrow \omega_t/\omega_{p1} \gg 1$

Postupak projektovanja

- Postoje razne metode
 - Minimalna potrošnja i dimenzije tranzistora
 - Tokom simulacija podešavati dimenzije kako bi se zadovoljili svi uslovi
- Mi ćemo koristiti metodu prikazanu u knjizi, Phillip E. Allen i Douglas R. Holberg, *CMOS Analog Circuit Design*

Važne relacije

- Brzina odziva $SR = \frac{I_5}{C_C}$
- Pojačanja prvog i drugog stepena

$$A_{V1} = -g_{m1} (r_{ds2} \parallel r_{ds4}) = \frac{-g_{m1}}{g_{ds2} + g_{ds4}} = \frac{-2g_{m1}}{I_5(\lambda_2 + \lambda_4)}$$

$$A_{V2} = -g_{m7} (r_{ds7} \parallel r_{ds6}) = \frac{-g_{m7}}{g_{ds7} + g_{ds6}} = \frac{-g_{m7}}{I_7(\lambda_7 + \lambda_6)}$$

- Proizvod pojačanja i propusnog opsega

$$GBW = \frac{g_{m1}}{C_C}$$

Važne relacije

- Učestanost pola p_1 : $\omega_{p2} \approx \frac{1}{g_{m7} R_1 R_2 C_C}$
- Učestanost pola p_2 : $\omega_{p2} \approx \frac{g_{m7}}{C_1 + C_2 + C_L} \approx \frac{g_{m7}}{C_L}$
- Učestanost RHP nule $\omega_z \approx \frac{-g_{m7}}{C_C}$
- Minimalna i maksimalna vrednost CMIR

$$V_{in}(\min) = V_{SS} + V_{t3\max} + \sqrt{\frac{I_{D5}}{\mu_n C_{ox} (W/L)_3}} - |V_{t1\min}|$$

$$V_{in}(\max) = V_{DD} - V_{SD5(sat)} - |V_{t1\max}| - \sqrt{\frac{I_{D5}}{\mu_p C_{ox} (W/L)_1}}$$

Proračun početnih vrednosti

- Tehnologija
 - AMS 0.35 μm CMOS
- Dužina kanala svih tranzistora:
 - $L=2*L_{min}=0,7 \mu\text{m}$
- Uslov da je fazna margina jednaka 60^0 , uz pretpostavku da je $\omega_z > 10^* \omega_t$ (zanemarena nula)

$$PM = \pm 180^0 - \text{Arg}[A(j\omega)F(j\omega)] =$$

$$= \pm 180^0 - \tan^{-1}\left(\frac{\omega}{|\omega_{p1}|}\right) - \tan^{-1}\left(\frac{\omega}{|\omega_{p2}|}\right) - \tan^{-1}\left(\frac{\omega}{|\omega_{z1}|}\right) = 60^0$$

Proračun početnih vrednosti

$$120^{\circ} = \tan^{-1}\left(\frac{GBW}{|\omega_{p_1}|}\right) + \tan^{-1}\left(\frac{GBW}{|\omega_{p_2}|}\right) + \tan^{-1}\left(\frac{GBW}{|\omega_{z_1}|}\right)$$

$$= \tan^{-1}(A_{v0}) + \tan^{-1}\left(\frac{GBW}{|\omega_{p_2}|}\right) + \tan^{-1}(0,1)$$

$$24,3^{\circ} = \tan^{-1}\left(\frac{GBW}{|\omega_{p_2}|}\right) \rightarrow |\omega_{p_2}| \geq 2,2 \cdot GBW \rightarrow \frac{g_{m7}}{C_L} \geq 2,2 \frac{g_{m1}}{C_C}$$

Na osnovu pretpostavke da je $\omega_z > 10 \cdot \omega_t$ ($\omega_t = GBW$), sledi

$$\frac{g_{m7}}{C_C} > 10 \frac{g_{m1}}{C_C} \rightarrow g_{m7} > 10 \cdot g_{m1}$$

$$C_C \geq 0,22 \cdot C_L = 0,22 \cdot 10 \text{ pF} = 2,2 \text{ pF} \rightarrow C_C = 3 \text{ pF}$$

Proračun početnih vrednosti

$$I_5 = C_C \cdot SR = 3 \text{ pF} \cdot 10 \frac{\text{V}}{\mu\text{s}} = 30 \mu\text{A}$$

$$\left(\frac{W}{L}\right)_3 = \frac{I_5}{K_{pn} [V_{in,\min} - V_{SS} + |V_{t1\min}| - V_{t3\max}]^2}$$

$$\left(\frac{W}{L}\right)_3 = \frac{30\mu}{170 \frac{\mu\text{A}}{\text{V}^2} [0,2 - 0 + 0,58 - 0,56]^2} = 3,64$$

$$\left(\frac{W}{L}\right)_3 = 4 \rightarrow W_{3,4} = 2,8 \mu\text{m}$$

- $K_{pn} = 170 \mu\text{A}/\text{V}^2$, $|V_{tp\min}| = 0,58 \text{ V}$, $|V_{tn\max}| = 0,56 \text{ V}$

Proračun početnih vrednosti

- Provera za treći pol koji nastaje zbog C_{gs3}

$$\omega_{p3} = -\frac{g_{m3}}{2 \cdot C_{gs3}} = -\frac{\sqrt{2 \cdot I_3 \cdot K_{pn} \cdot \left(\frac{W}{L}\right)_3}}{2 \cdot \frac{2}{3} \cdot W_3 \cdot L_3 \cdot C_{ox}} =$$

$$\omega_{p3} = -\frac{\sqrt{2 \cdot 15 \mu A \cdot 170 \mu A / V^2 \cdot 4}}{2 \cdot \frac{2}{3} \cdot 2,8 \mu m \cdot 0,7 \mu m \cdot 4,54 \text{ fF} / \mu m^2} = -12,04 \cdot 10^9 \frac{\text{rad}}{\text{s}}$$

$$f_{p3} = 1,92 \text{ GHz} \gg 10 \text{ GBW}$$

Proračun početnih vrednosti

$$g_{m1} = GBW \cdot C_C = 2 \cdot \pi \cdot 10 \cdot 10^6 \cdot 3 \cdot 10^{-12} = 188,5 \mu\text{S}$$

$$\left(\frac{W}{L}\right)_1 = \frac{g_{m1}^2}{2 \cdot K_{pp} \cdot I_1} = 20,42 \rightarrow \left(\frac{W}{L}\right)_1 = 20 \rightarrow W_{1,2} = 14 \mu\text{m}$$

$$V_{SD,sat5} = VDD - V_{in,max} - |V_{t1max}| - \sqrt{\frac{I_5}{K_{pp} \cdot \left(\frac{W}{L}\right)_1}} = 0,36 \text{ V}$$

$$\left(\frac{W}{L}\right)_5 = \frac{2 \cdot I_5}{K_{pp} \cdot V_{SD}^2} = 7,98 \rightarrow \left(\frac{W}{L}\right)_5 = 8 \rightarrow W_5 = 5,6 \mu\text{m}$$

- $K_{pp} = 58 \mu\text{A/V}^2$, $|V_{tpmax}| = 0,78 \text{ V}$, $|V_{tnmax}| = 0,56 \text{ V}$

Proračun početnih vrednosti

- Pri uslovu i proračunu za faznu marginu

$$PM = 60^{\circ} \rightarrow \omega_{p2} \geq 2,2 \cdot GBW$$

$$\omega_{p2} = \frac{g_{m7}}{C_1 + C_2 + C_L} \approx \frac{g_{m7}}{C_L} \gg \frac{2,2 \cdot g_{m1}}{C_C}$$

korišćena je pretpostavka

$$\omega_z \geq 10 \cdot GBW \rightarrow g_{m7} \geq 10 \cdot g_{m1} = 1,885 \text{ mS}$$

Proračun početnih vrednosti

$$V_{GS4} = V_{GS7} \rightarrow \left(\frac{W}{L}\right)_7 = \frac{g_{m7}}{g_{m4}} \cdot \left(\frac{W}{L}\right)_4 = 52,79$$

$$\text{gde je } g_{m4} = \sqrt{2 \cdot K_{pn} \cdot I_4 \cdot \left(\frac{W}{L}\right)_4} = 142,82 \mu\text{S}$$

$$\left(\frac{W}{L}\right)_7 = 52 \rightarrow I_7 = \frac{g_{m7}^2}{2 \cdot K_{pn} \cdot \left(\frac{W}{L}\right)_7} \approx 200,97 \mu\text{A}$$

$$\left(\frac{W}{L}\right)_6 = \left(\frac{W}{L}\right)_5 \frac{I_7}{I_5} = 53,59$$

$$\left(\frac{W}{L}\right)_{6,7} = 54 \rightarrow W_{6,7} = 37,8 \mu\text{m}$$

Proračun početnih vrednosti

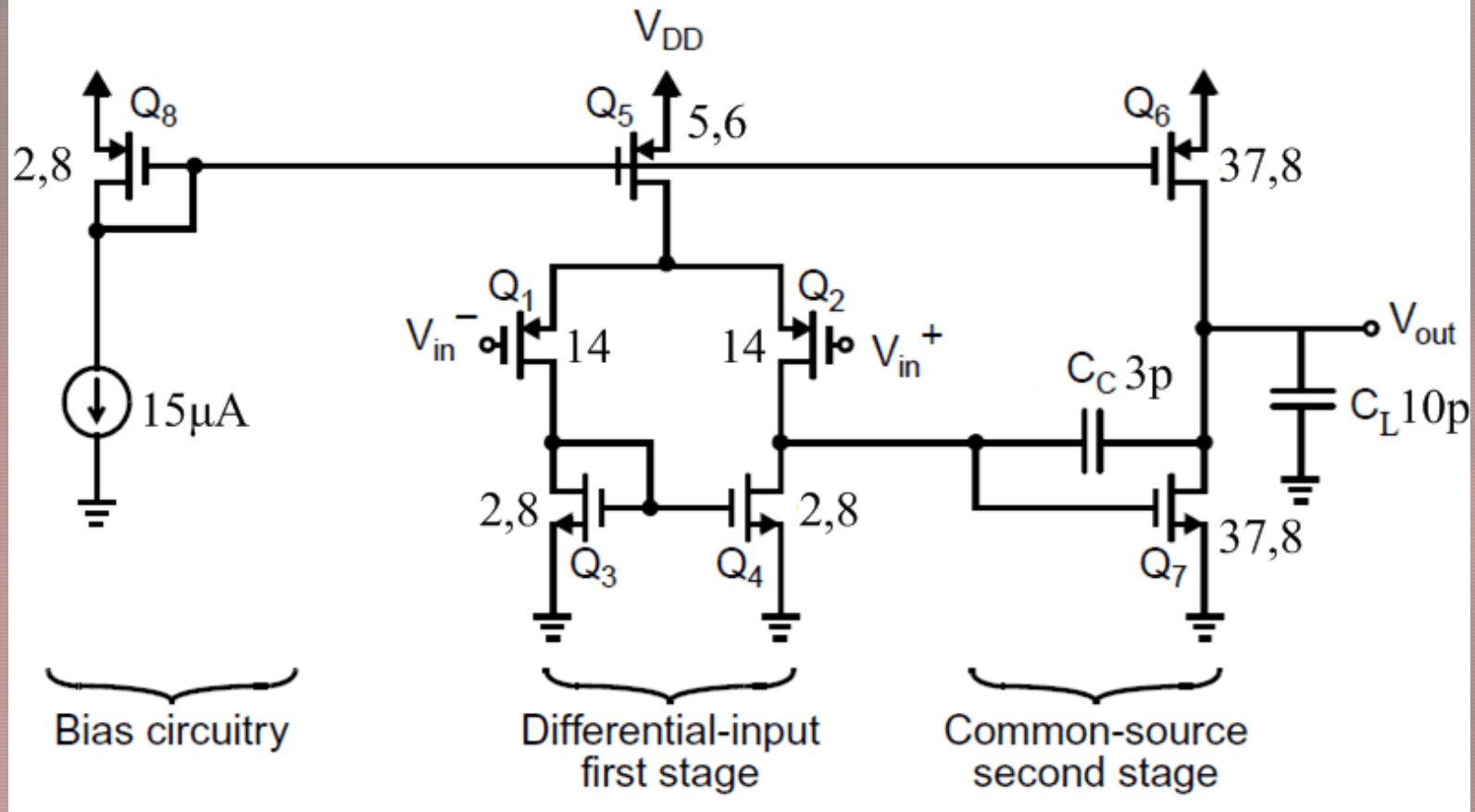
$$V_{out,min} = V_{DS7,sat} = \sqrt{\frac{2 \cdot I_7}{K_{pn} \cdot \left(\frac{W}{L}\right)_7}} = 0,209 \text{ V}$$

$$P_{diss} = 3,3 \cdot (15\mu + 30\mu + 200,97\mu) = 0,812 \text{ mW} < 1,5 \text{ mW}$$

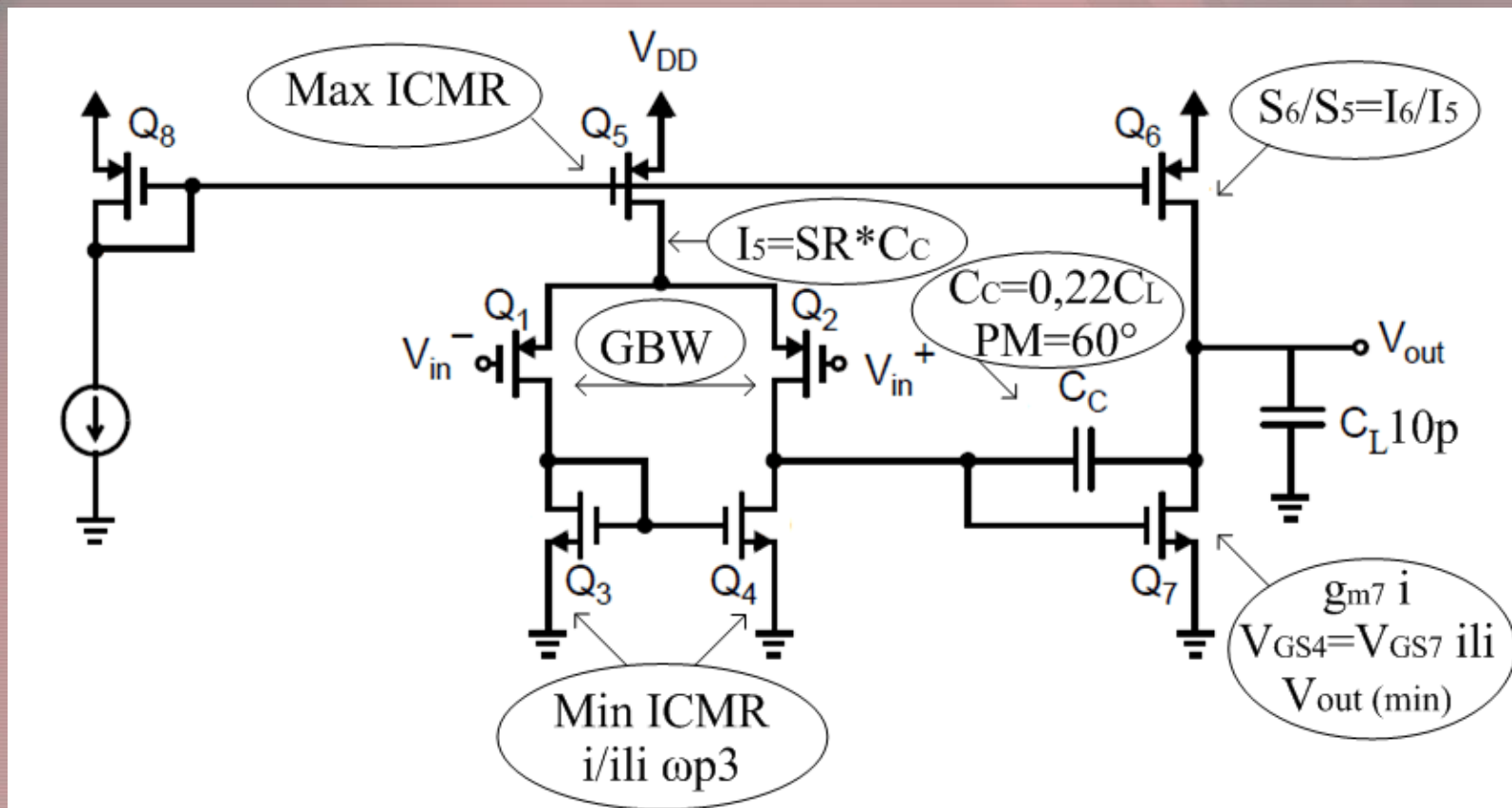
$$A_{V1} = \frac{2 \cdot g_{m1} \cdot g_{m7}}{I_5 \cdot (\lambda_2 + \lambda_4) \cdot I_7 \cdot (\lambda_6 + \lambda_7)} =$$
$$= \frac{2 \cdot 188,5 \cdot 10^{-6} \cdot 1,885 \cdot 10^{-3}}{30 \cdot 10^{-6} \cdot (0,06 + 0,022) \cdot 200,97 \cdot 10^{-6} \cdot (0,022 + 0,06)}$$

$$A_{V1} = 17529,62 (\approx 85\text{dB})$$

Dvostepeni operacioni pojačavač



Dvostepeni operacioni pojačavač



Dvostepeni operacioni pojačavač

| | Drain Current | | Q1 and Q2 | | Q3 and Q4 | | Inverter | Inverter Load | | Compensation Capacitor |
|-------------------------|--------------------|--------------------|--------------------|---|-----------|---|--------------------------------|----------------|----------------|------------------------|
| | I ₅ | I ₇ | W/L | L | W | L | W ₇ /L ₇ | W ₆ | L ₆ | C _c |
| Increase dc Gain | (↓) ^{1/2} | (↓) ^{1/2} | (↑) ^{1/2} | ↑ | | ↑ | (↑) ^{1/2} | | ↑ | |
| Increase GB | (↑) ^{1/2} | | (↑) ^{1/2} | | | | | | | ↓ |
| Increase RHP Zero | | (↑) ^{1/2} | | | | | (↑) ^{1/2} | | | ↓ |
| Increase Slew Rate | ↑ | | | | | | | | | ↓ |
| Increase C _l | | | | | | | | | | ↓ |

Zavisnost performansi operacionog pojačavača od dc struja, dimenzija tranzistora i kompenzacionog kondenzatora