UiO : Department of Informatics
University of Oslo

IN4180 - Analog Microelectronics Design

Basic Operational Amplifier Design and Compensation - Part 2
Compensation and stability

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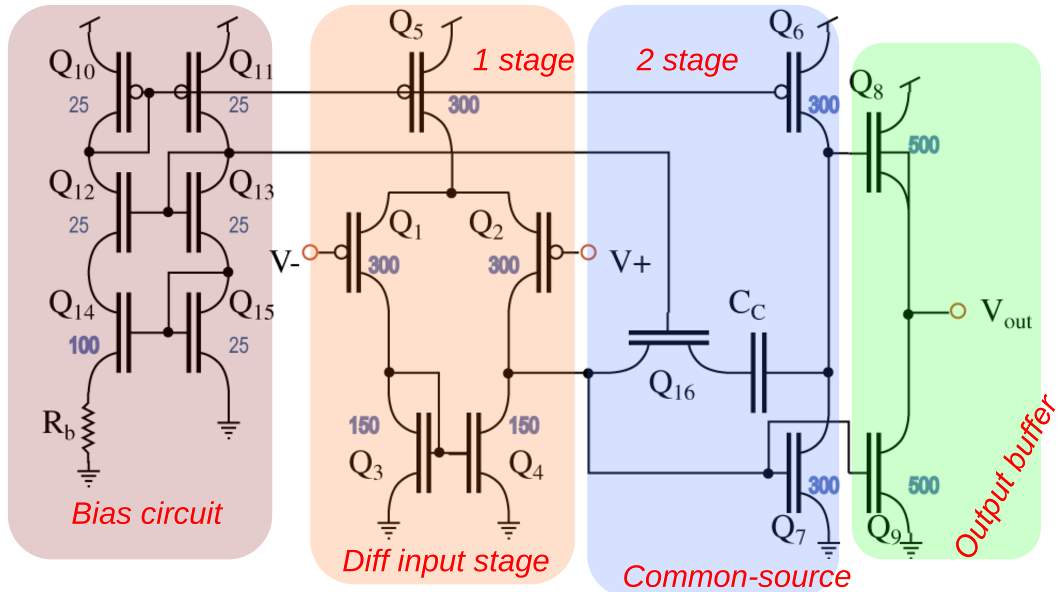
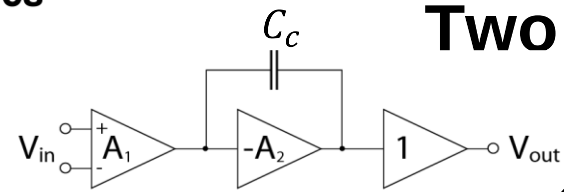
CMOS OPAMP topology



- PMOS diff input stage
- Numbers realistic transistor widths
  - Length 1-2 times minimum
- Output buffer may not be needed for capacitive loads

Two stage opamp gain



- Gain for diff pair – 1. stage

$$A_{v1} = g_{m1}(r_{ds2}||r_{ds4})$$

  - Typical gain 50-100

- Gain of common source – 2. stage

$$A_{v2} = -g_{m7}(r_{ds6}||r_{ds7})$$

  - Typical gain 50-100

- Gain of source follower – output buffer

$$A_{v3} = \frac{g_{m8}}{G_L + g_{m8} + g_{s8} + g_{ds8} + g_{ds9}}$$

  - Gain ≈1
  - Not needed for capacitive loads

$$g_{m1} = \sqrt{2\mu_n C_{ox}\frac{W}{L}I_D} = \sqrt{2\mu_n C_{ox}\frac{W}{L}\frac{I_{bias}}{2}}$$

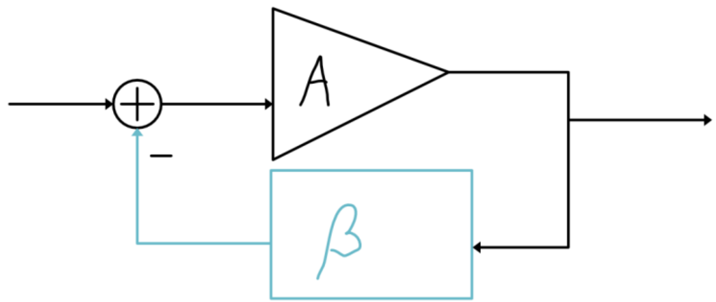
$$\lambda = \frac{k_{ds}}{2L\sqrt{V_{DS} - V_{eff} + \Phi_0}}$$

$$k_{ds} = \sqrt{\frac{2K_s\varepsilon_0}{qN_A}}$$

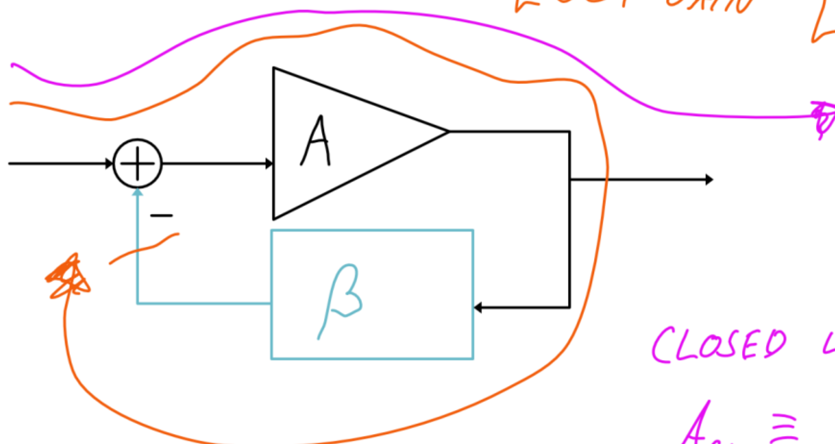
$$r_{ds} \cong \frac{1}{\lambda I_D}$$

$$g_{s8} = \frac{\gamma g_m}{2\sqrt{V_{SB} + |2\varphi_F|}}$$

Feedback stability



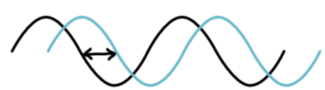
Feedback stability



LOOP GAIN $L \equiv A\beta$

CLOSED LOOP GAIN

$$A_{CL} \equiv \frac{A}{1 + A\beta}$$



$\angle L(\omega_t) > -180°$

STABLE!!

$\angle L(\omega_t) < -180°$

UNSTABLE!!

Frequency response – First order model

Midband frequencies

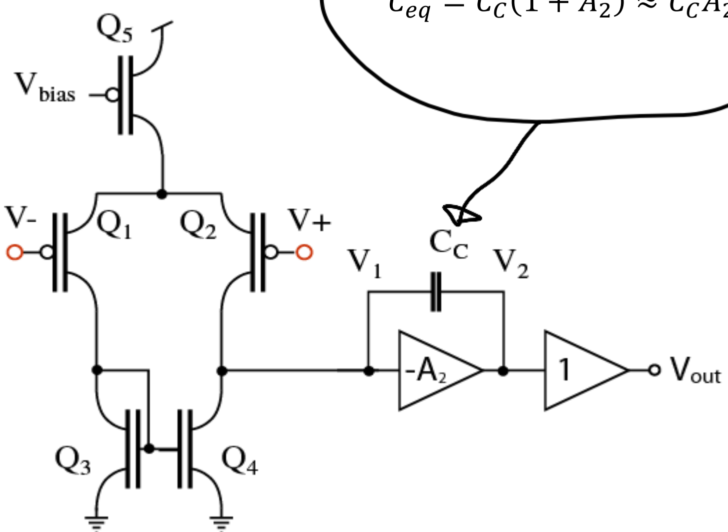
- C_{eq} dominates

$$A_1 = g_{m1} Z_{out1}$$
$$= g_{m1}\left(r_{ds2} || r_{ds4} || \frac{1}{sC_{eq}}\right)$$

at midband freq C_{eq} dominates

$$A_1 = g_{m1}\frac{1}{sC_{eq}} = g_{m1}\frac{1}{sC_C A_2}$$

$$C_{eq} = C_C(1 + A_2) \approx C_C A_2$$



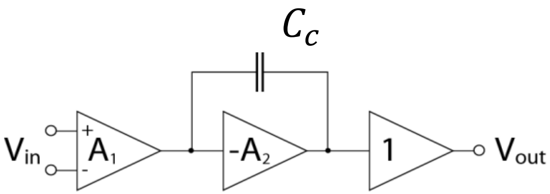
$$A_v = \frac{v_{out}}{v_{in}} = A_1 A_2 A_3 \approx g_{m1}\frac{1}{sC_C A_2}\cdot A_2 \cdot 1 = \underline{\frac{g_{m1}}{sC_C}}$$

$$\omega_{ta} = \frac{g_{m1}}{C_C} = \frac{I_{D5}}{V_{eff1} C_C}$$

Unit-gain frequency proportional to g_m assuming A_3=1

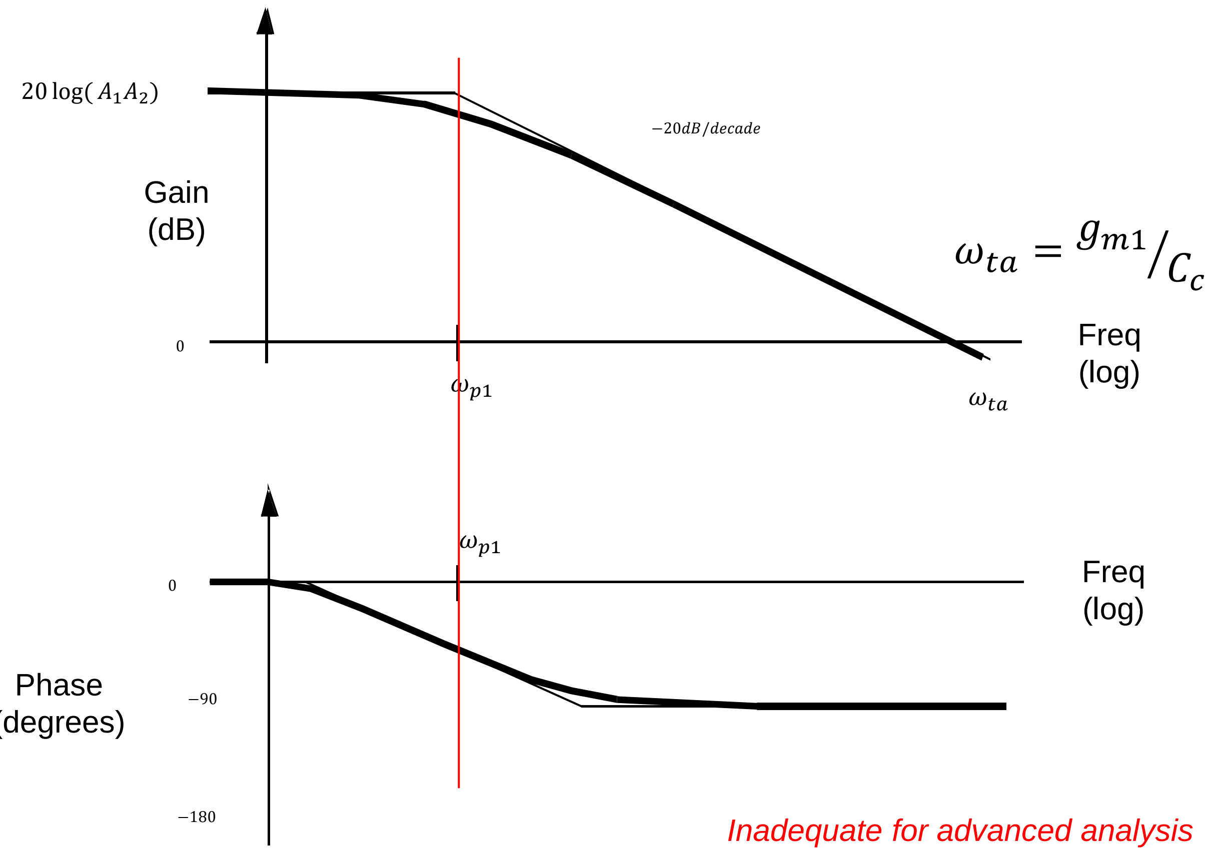
setting $|A_V(j\omega_{ta})| = 1$ *and solve*

Frequency response - First order model



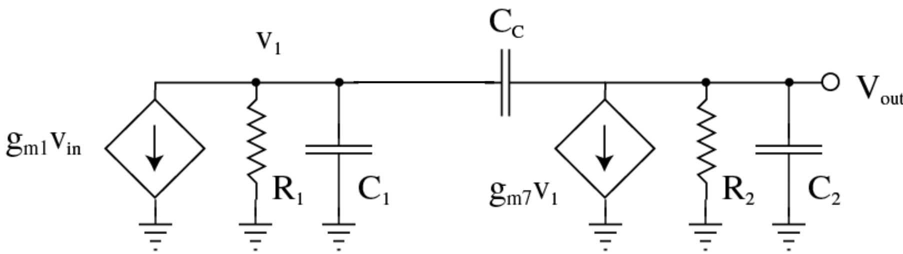
Midband frequencies

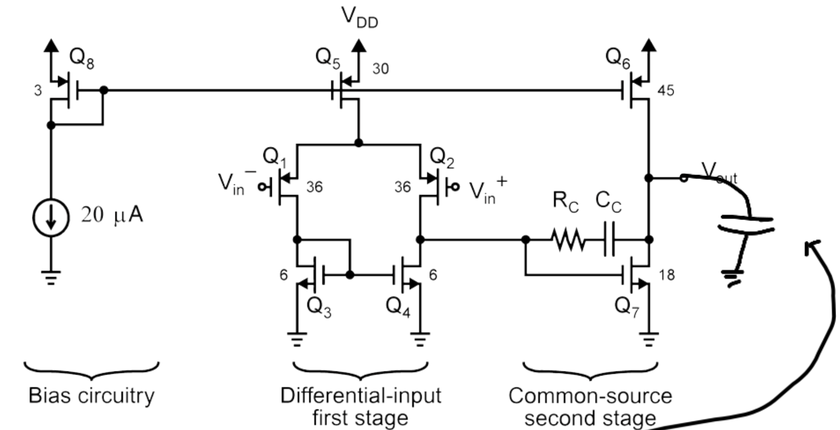
- Below unit-gain frequency
- Above frequencies without compensation effects
- Ignore all C except C_c
- Ignore R_c which only has effect at ω_{ta}



Inadequate for advanced analysis

Frequency response Second order model





$R_1 = r_{ds4}||r_{ds2}$ and $C_1 = C_{db2} + C_{db4} + C_{gs7}$

$R_2 = r_{ds6}||r_{ds7}$ and $C_2 = C_{db7} + C_{db6} + C_{L2}$

- Assume R_C=0 give transfer function

$$\frac{v_{out}}{v_{in}} = \frac{g_{m1}g_{m7}R_1R_2\left(1 - \frac{sC_C}{g_{m7}}\right)}{1 + sa + s^2 b}$$

$$a = (C_1 + C_C)R_2 + (C_1 + C_C)R_1 + g_{m7}R_1R_2C_C$$

$$b = R_1R_2(C_1C_2 + C_1C_C + C_2C_C)$$

- Assume widely separated poles

$$D(s) = \left(1 + \frac{s}{\omega_{p1}}\right)\left(1 + \frac{s}{\omega_{p2}}\right) \approx 1 + \frac{s}{\omega_{p1}} + \frac{s^2}{\omega_{p1}\omega_{p2}}$$

- Dominant pole

$$\omega_{p1} = \frac{1}{R_1[C_1 + C_C(1 + g_{m7}R_2)] + R_2(C_1 + C_C)} \approx \frac{1}{R_1 C_C(1 + g_{m7}R_2)} \approx \frac{1}{g_{m7}R_1R_2C_C}$$

- Non-dominant pole

$$\omega_{p2} = \frac{g_{m7}C_C}{C_1C_2 + C_1C_C + C_2C_C} \approx \frac{g_{m7}}{C_1 + C_2}$$

- *Increasing g_{m7} → increased pole distance*
- *Pole splitting compensation*
- *Cc may decrease ω_{p1}*

- Additional zero

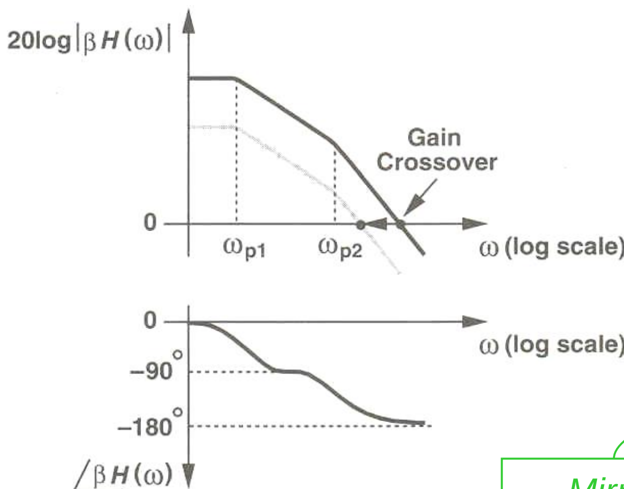
$$\frac{v_{out}}{v_{in}} = \frac{g_{m1} g_{m7} R_1 R_2 \left(1 - \frac{sC_C}{g_{m7}}\right)}{1 + sa + s^2 b} \qquad \Rightarrow \omega_Z = -\frac{g_{m7}}{C_C}$$

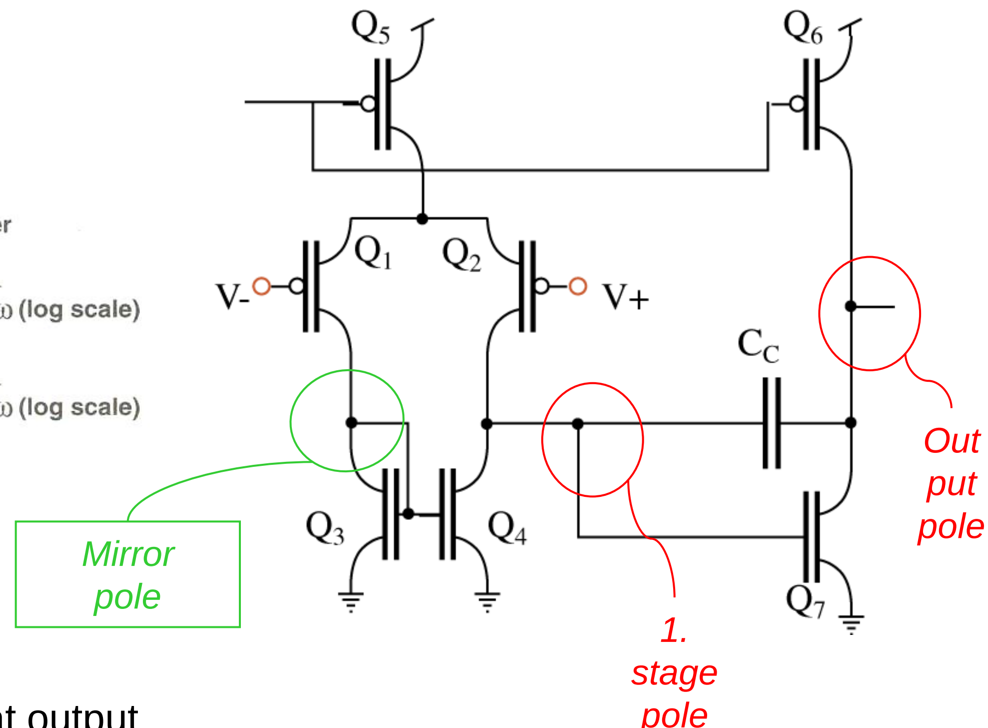
  - Right half-plane→negative phase shift with decreased PM
  - Stability issues

– Hard to get rid of, but pole distance is increased with g_{m7}

Two-pole amplifier

- Dominant poles of two-stage amps



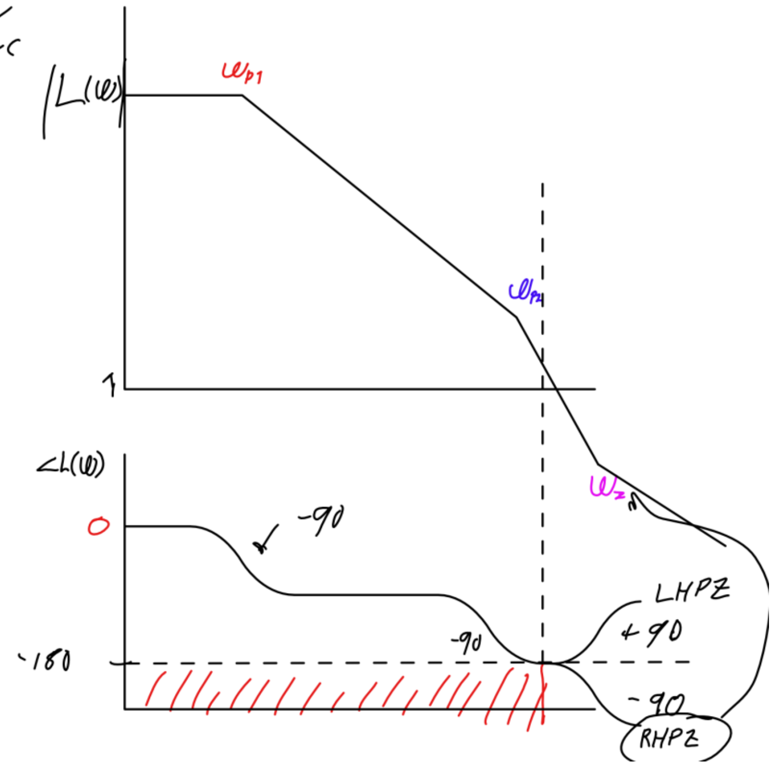


  - 1. stage
    - High gain
    - Dominant pole at output

$$\omega_{p1} = \frac{1}{g_{m7} R_1 R_2 C_c}$$

$$\omega_{p2} = \frac{g_{m7}}{C_1 + C_2}$$

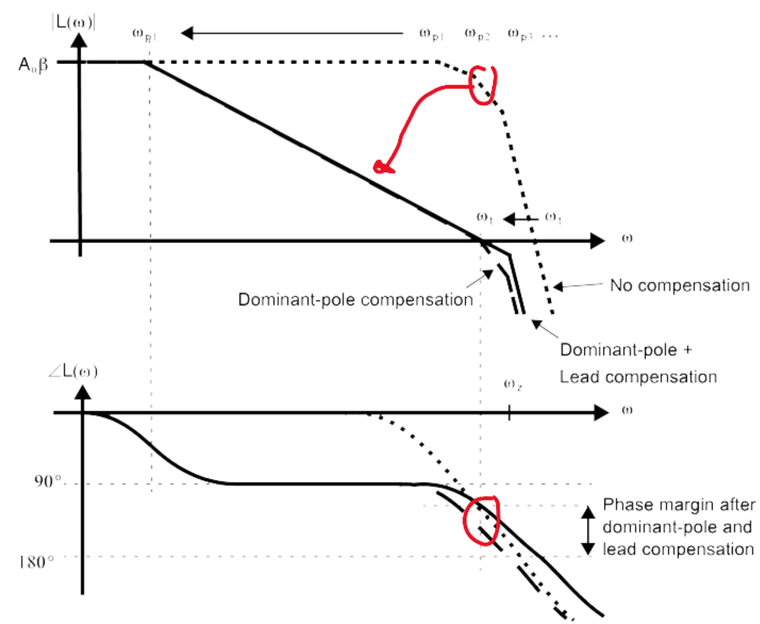
$$\omega_z = \frac{-g_{m7}}{C_c}$$



Opamp compensation

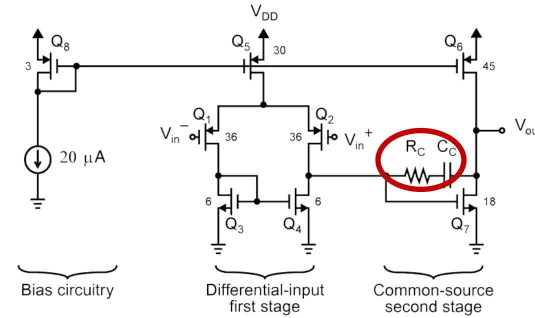
Dominant pole comp using miller Cc

- Dominant-pole compensation
  - Forcing a feedback system to have 1. order response up to loop unit-gain frequency ω_t
  - First order system unconditional stable with > 90 phase margin
- Lead compensation
  - Adding zero, ω_z, just above ω_t
  - May improve PM with 20°



Lead comp using Rc

$$\frac{v_{out}}{v_{in}} = \frac{g_{m1}g_{m7}R_1R_2\left(1-\frac{sC_C}{g_{m7}}\right)}{1+sa+s^2b} \qquad \Rightarrow \omega_Z = -\frac{g_{m7}}{C_C}$$



- Have to make $R_C > 0$
  - Zero with some resistive element

$$\omega_Z = -\frac{1}{C_C(1/g_{m7} - R_C)}$$

  - May eliminate that zero by setting $$R_C = \frac{1}{g_{m7}}$$
  - Alternatively try to cancel ω_{p2} with ω_z

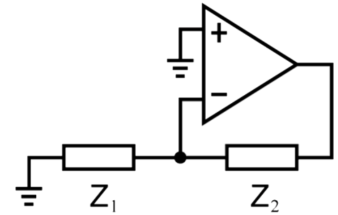
$$\frac{g_{m7}}{C_1 + C_2} = -\frac{1}{C_C(1/g_{m7} - R_C)} \Rightarrow R_C = \frac{1}{g_{m7}}\left(1 + \frac{C_1 + C_2}{C_C}\right)$$

  - "Overcompensation" might even be wise: $\omega_Z = 1.7\omega_t$

$$R_C >> 1/g_{m7} \Rightarrow \omega_Z \approx \frac{1}{R_C C_C} \qquad \omega_t \approx g_{m7}/C_C \text{ gives } R_C = \frac{1}{1.7g_{m7}}$$

Compensation procedure

$\beta = 1$ (max feedback)



$$L(s) \approx A(s)\frac{Z_1}{Z_1 + Z_2}$$

$$\beta = \frac{Z_1}{Z_1+Z_2}$$

Dominant pole

– From **first order** model C_C and ω_t is given as:

$$\omega_t = L_0\omega_{p1} = \beta\frac{g_{m1}}{C_C}$$

UGF

- Find **initial** C_C setting unit-gain frequency close to second pole

$$\beta\frac{g_{m1}}{C_C} = \frac{g_{m7}}{C_1 + C_2} = \frac{g_{m7}}{C_L}$$

$$\downarrow$$

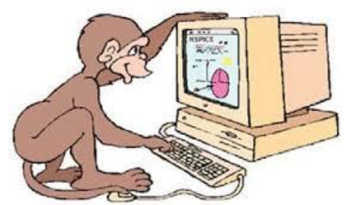
$$C_C' = \left(\beta\frac{g_{m1}}{g_{m7}}\right)C_L$$

UGF Cc -> wp2

Opamp compensation design stategy

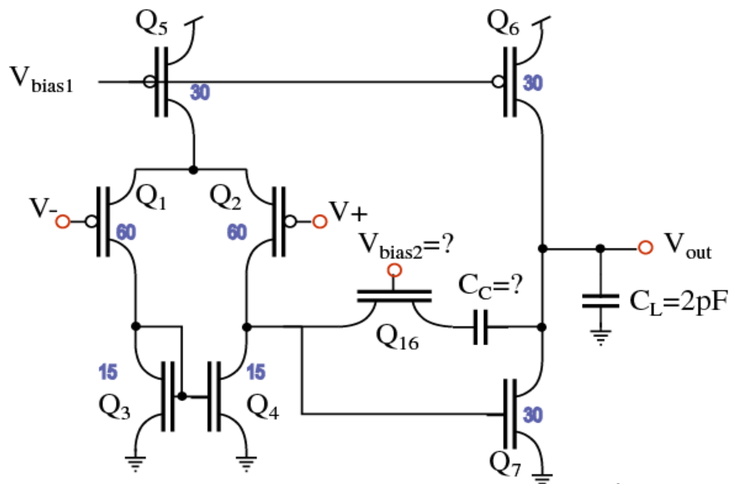
1. Start with $C_C' = \left(\beta \frac{g_{m1}}{g_{m7}}\right) C_L$ setting unit-gain frequency close to second pole
2. By simulation (SPICE, CADENCE) find frequency with -125° phase shift (called gain A') - This is our unit gain frequency ω_t target
3. Choose new C_C such that ω_t is unit-gain freq of L(s)
   - $C_C = C_C' A'$ giving 55° phase margin
   - A couple of simulation iterations may be necessary
4. Choose R_C : $$R_C = \frac{1}{1.7\omega_t C_C}$$ *Almost optimum lead compensation for any opamp*
   - Giving phase margin of 85° (+30°) leaving 5° for variations

1. Sometimes phase margins are not adequate, then increase C_C
2. Replace R_C with a transistor $$R_C = \frac{1}{\mu_n C_{ox} \left(\frac{W}{L}\right)_{16} V_{eff16}}$$



Opamp compensation Cadence example

- Find best compensation network C_c and R_c for:



AMS 0.35um technology

- New simulation with Cc=1.9pF give
  - ω_t=44.7MHz with A'=1.32

$$C_C = C_C' A' = 1.3pF \cdot 1.32 \approx 2.5pF$$

- New simulation with Cc=2.5pF give
  - ω_t=41MHz with A'=1.2

$$C_C = C_C' A' = 2.5pF \cdot 1.2 \approx 3.1pF$$

- New simulation with Cc=3.1pF give
  - ω_t=37.7MHz with A'=1.00

Marker at 55 deg phase margin

- Finding Rc

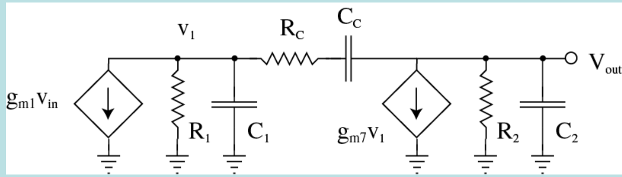
$$R_C = \frac{1}{1.2\omega_t C_C} = \frac{1}{1.2 \cdot 37.7 \cdot 10^6 \cdot 3.1 \cdot 10^{-12}} \approx 7132\Omega$$

Compensation procedure

Lead compensation - controlling Zero

$$\omega_z \approx \frac{-1}{C_C\left(\frac{1}{g_{m7}} - R_C\right)}$$

Two stage opamp small signal model



Several possibilities for R_C :

$$R_C = \frac{1}{g_{m7}} \;\; -> \omega_z = \infty$$

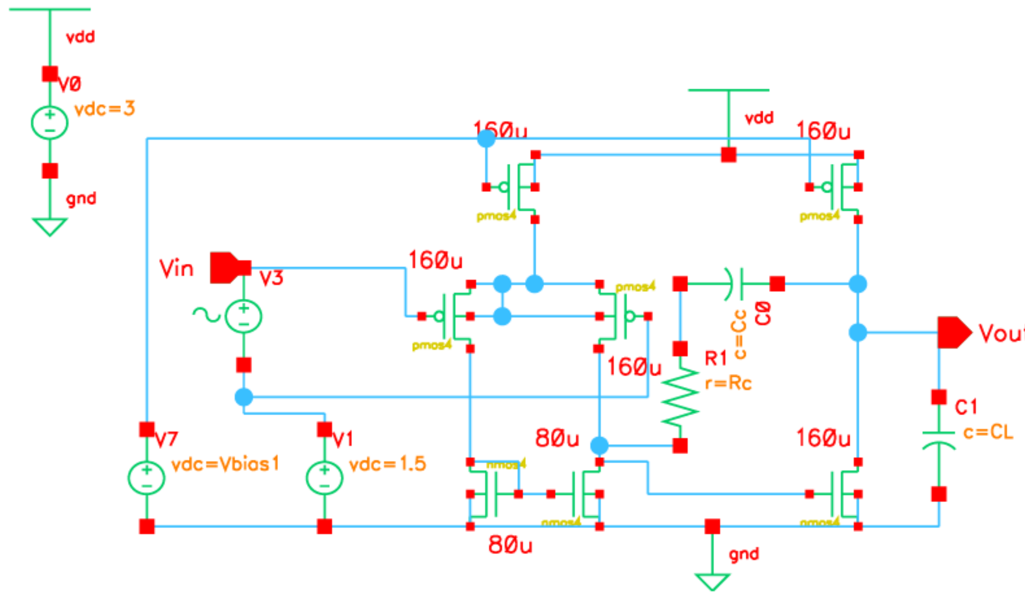
$R_C > \frac{1}{g_{m7}}$ RHPZ -> LHPZ and cancel ω_{p2}

$R_C \gg \frac{1}{g_{m7}}$ Moving LHPZ to a frequency slightly higher than ω_t $(wo\ R_C)$

Recommended to get more PM (20-30 degrees)

$$\omega_{p2} = \frac{g_{m7}C_C}{C_1C_2 + C_1C_C + C_2C_C} = \frac{-1}{C_C\left(\frac{1}{g_{m7}} - R_C\right)} \Rightarrow R_C = \frac{1}{g_{m7}}\left(1 + \frac{C_1 + C_2}{C_C}\right)$$

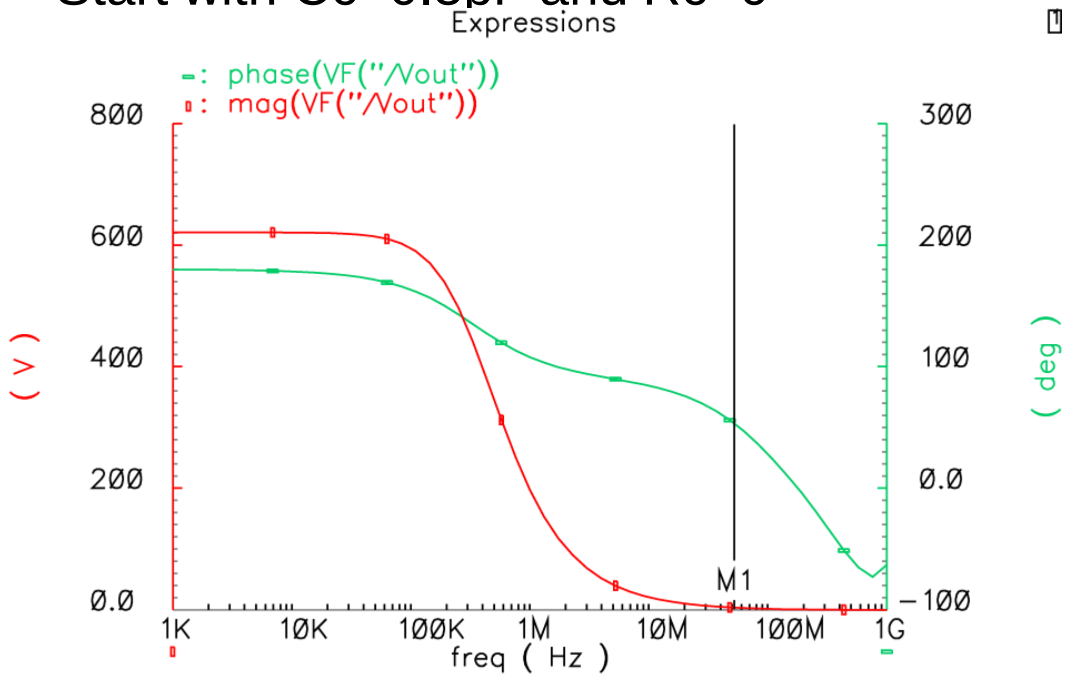
Find bias voltage:



Vbias1=2.3V give 84μA tail current

Found by simple simulation run displaying tail current

- Start with Cc=0.5pF and Rc=0



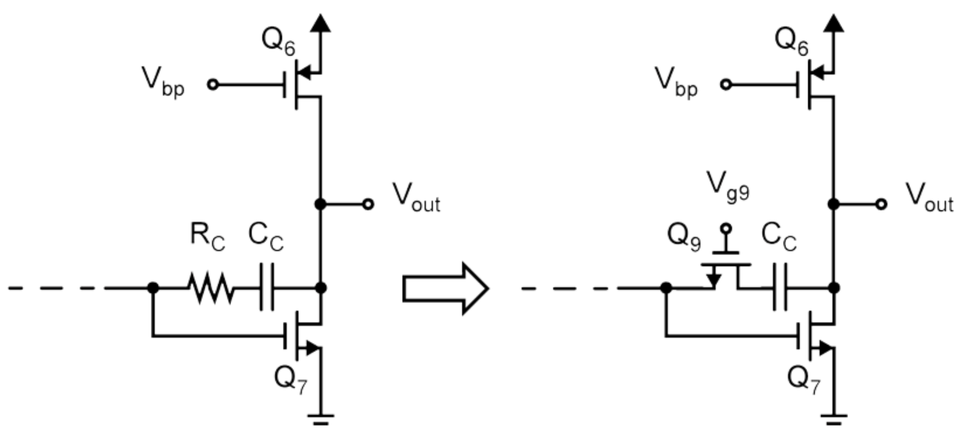
0° phase in CADENCE display is -180° actual phase shift

Find (180-125)=55° phase shift at ωt=50.1MHz with gain A'=3.7

$$C_C = C_C' A' = 0.5pF \cdot 3.7 \approx 1.9pF$$

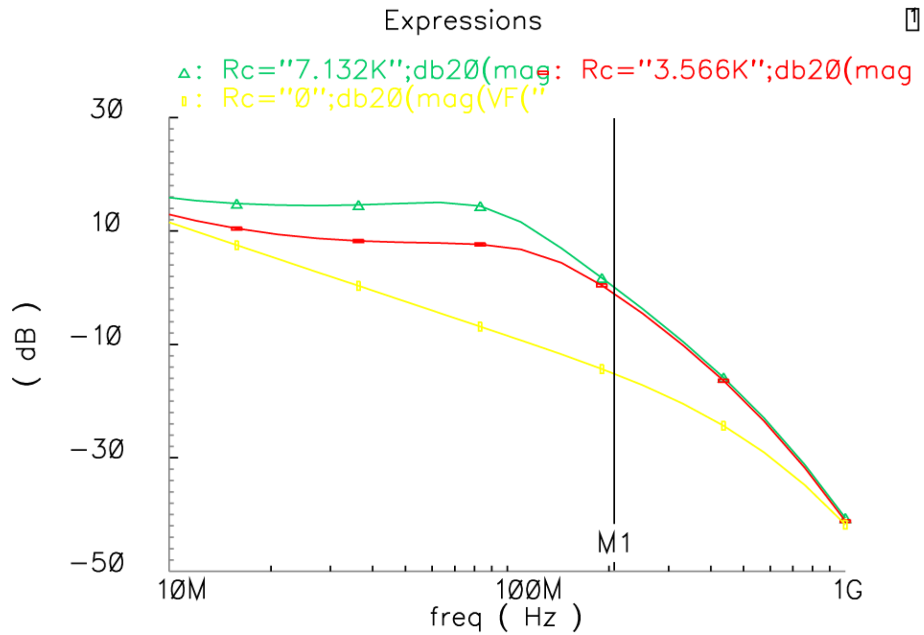
R_C as transistor

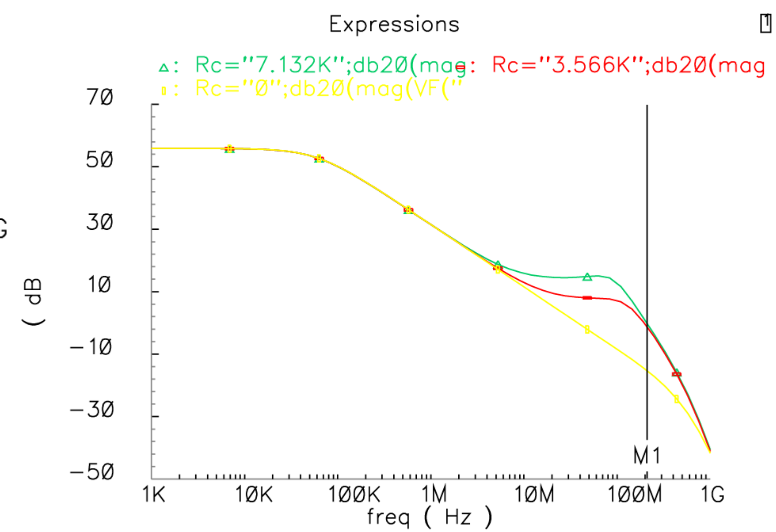
- Compensation resistor
  - Replaced by transistor in triode region



$$R_C = r_{ds} = \frac{1}{\mu_n C_{ox} \frac{W}{L} V_{eff}}$$

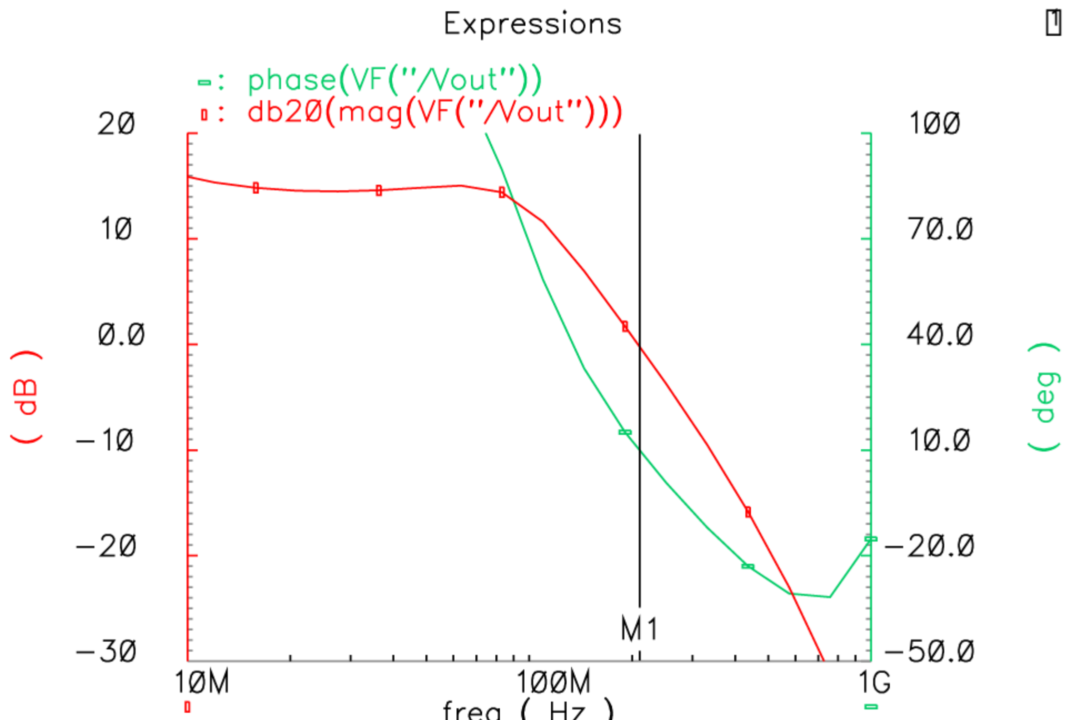
- Adding compensation resistor Rc





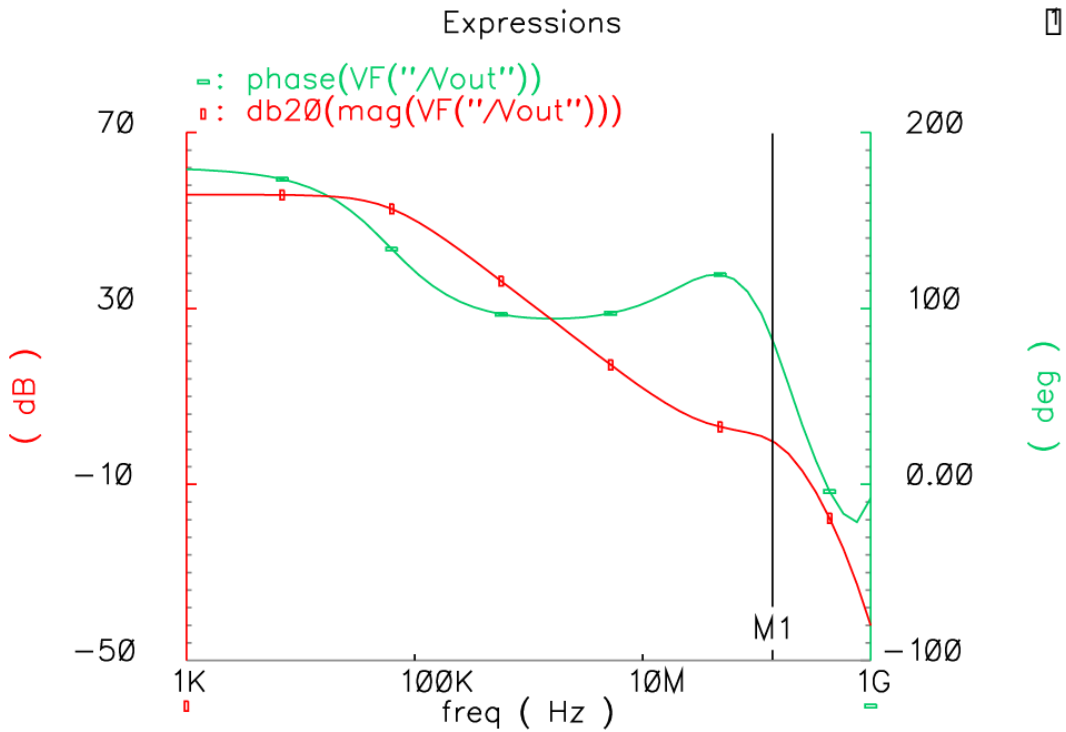
Give unit-gain freq of 209MHz

Phase margins?



Phase margins only 10° !!!

- What to do?
  - Book: increase Cc
  - Try to decrease Rc



Give unit-gain freq of 133MHz with PM=84° with Rc=2050Ω