

EE 610: Analog IC Design

Differential Amplifiers: MOS Loads

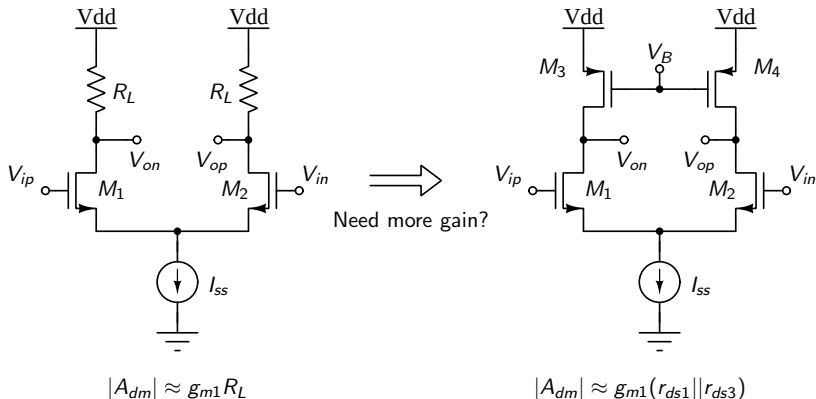
Nagarjuna Nallam

Department of EE, IIT Kanpur, India

Topics

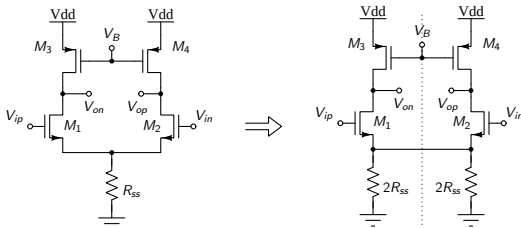
- ▶ Differential amplifier with current source load
- ▶ Common-mode feedback in fully-differential amplifiers
- ▶ Telescopic and folded cascodes
- ▶ Differential to single-ended conversion

Differential Amplifier with Current Source Load (DACSL)



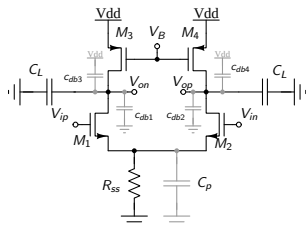
Why not to increase R_L to increase A_{dm} ?

DACSL: Small-signal analysis



DM equivalent half circuit	CM equivalent half circuit
$ A_{dm} \approx g_{m1}(r_{ds1} r_{ds3})$	$ A_{cm} \approx g_{m1}r_{ds3}/(1 + 2g_{m1}R_{ss})$

DACSL: Frequency Response



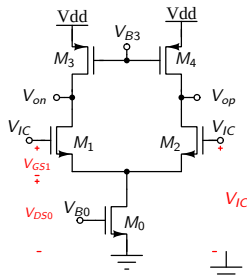
Neglected c_{gd} of all transistors

DM equivalent half circuit	CM equivalent half circuit
$\omega_{p1} \approx 1 / ((r_{ds1} r_{ds3}) C'_L)$ $C'_L = C_L + c_{db1} + c_{db3}$ $ A_{dm} \approx \frac{g_{m1}(r_{ds1} r_{ds3})}{1 + s / \omega_{p1}}$	$Z_{ss} = \frac{2R_{ss}}{1 + s(R_{ss}C_P)}$ $C'_L = C_L + c_{db1} + c_{db3}$ $ A_{cm} \approx \frac{g_{m1}(r_{ds1} r_{ds3})}{(1 + 2g_{m1}Z_{ss})(1 + s / \omega_{p1})}$

DACSL: Input common-mode range

$$\begin{aligned} V_{GS1,min} &= V_{TH1} + V_{DS1,min} \\ &= V_{TH1} + \sqrt{\frac{I_{SS}}{\mu_n C_{ox} (W/L)_1}} \end{aligned}$$

$$\begin{aligned} V_{DS0,min} &= V_{B0} - V_{TH0} \\ &= \sqrt{\frac{2I_{SS}}{\mu_n C_{ox} (W/L)_0}} \end{aligned}$$

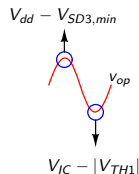


$$V_{IC,min} = V_{GS1,min} + V_{DS0,min}$$

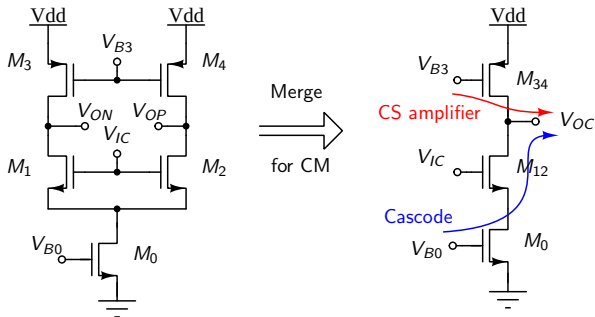
$$V_{IC} - V_{TH1} < V_{dd} - |V_{DS3}| \Rightarrow V_{IC,max} = V_{dd} - |V_{DS3,min}| + V_{TH1} \quad \leftarrow \text{can be } > V_{dd}$$

Remember: For a current source, V_{DS} can be $\geq (V_{DS,min} = V_{GS} - V_{TH})$

Output swing:



DACSL: Biasing



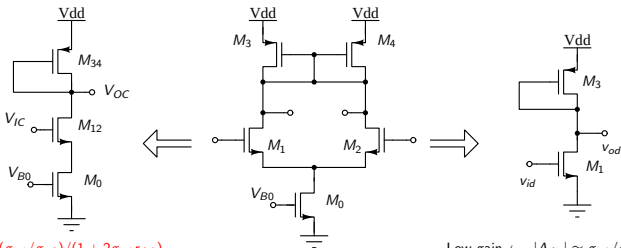
Even if we manage to keep all transistors in saturation, a small change in

V_{B0} or V_{B3} , saturates V_{OC} ! $\Delta V_{OC} \approx -(g_{m3}r_{ds3})\Delta V_{B3}$

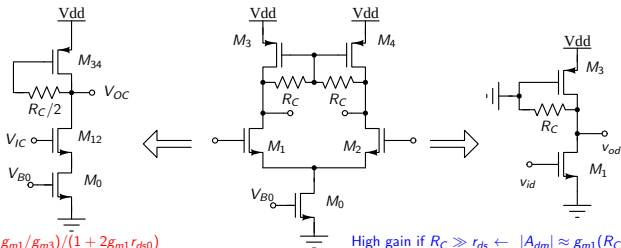


Output common-mode is not stable.

Two ways to resolve the biasing issue: Self-bias

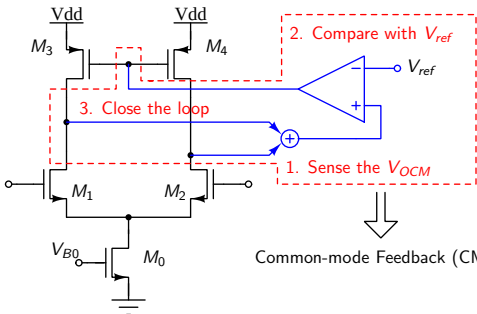


$$|A_{cm}| \approx (g_{m1}/g_{m3})/(1 + 2g_{m1}r_{ds0})$$



$$|A_{cm}| \approx (g_{m1}/g_{m3})/(1 + 2g_{m1}r_{ds0})$$

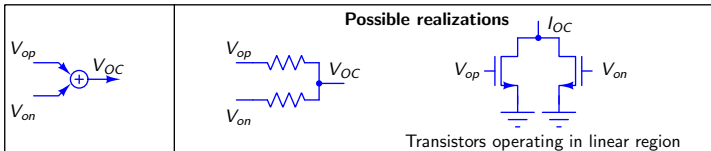
General way to resolve the biasing issue: CMFB



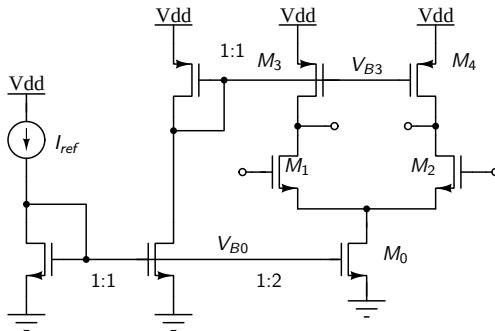
Requirements of CMFB:

1. $(GBW)_{CM} > (GBW)_{DM}$
2. Lower power consumption

Common-mode Feedback (CMFB)

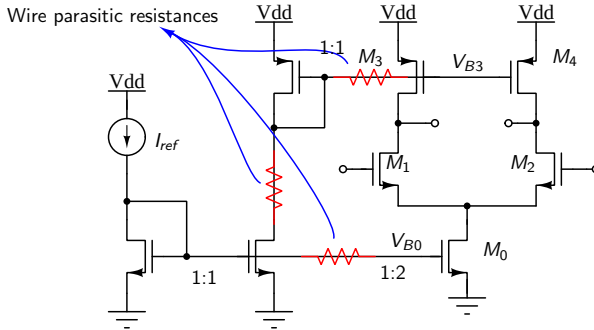


DACSL: Misconceptions about the bias stability



All device sizes are perfectly adjusted to have $V_{OC} = V_{dd}/2$. CMFB is not required.

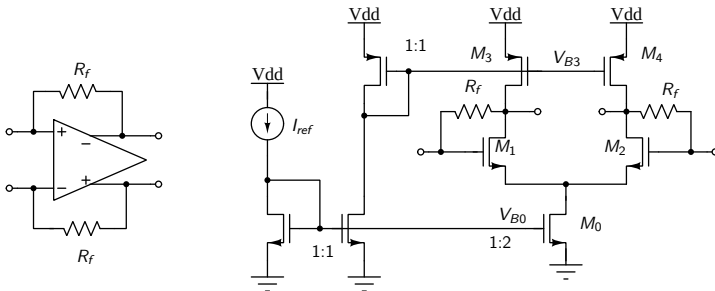
DACSL: Misconceptions about the bias stability



~~All device sizes are perfectly adjusted to have $V_{OC} = V_{dd}/2$. CMFB is not required.~~

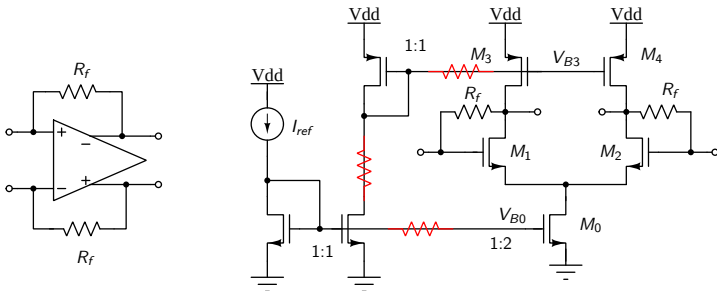
If V_{B3} is 10 mV smaller than the required value due to systematic/random mismatches then V_{OC} rises by 0.5 V. ← Assuming $g_{m3}r_{ds3} \approx 50$.

DACSL: Misconceptions about the bias stability



We are going to use the opamp in feedback as shown above. The common-mode voltage is automatically set by the (differential) feedback loop. We don't need CMFB.

DACSL: Misconceptions about the bias stability

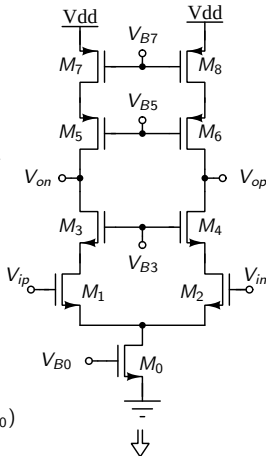
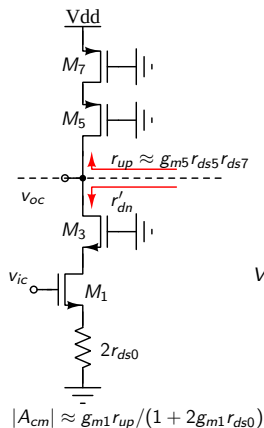


~~We are going to use the opamp in feedback as shown above. The common-mode voltage is automatically set by the (differential) feedback loop. We don't need CMFB.~~

Mismatches can still push V_{OC} towards V_{dd} or GND. The adjustment of either V_{B3} or V_{B0} is required.

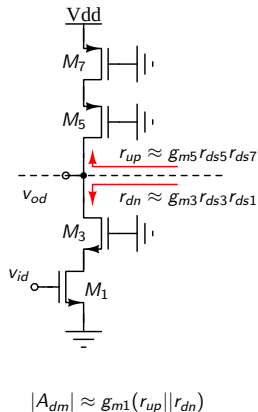
Fully-differential telescopic cascode amplifier

Small-signal CM equivalent



Not much improvement in CMRR.

Small-signal DM equivalent



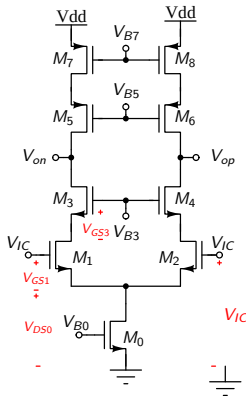
Fully-differential telescopic cascode amplifier

$$V_{GS1,min} = V_{TH1} + V_{DS1,min}$$

$$= V_{TH1} + \sqrt{\frac{I_{SS}}{\mu_n C_{ox} (W/L)_1}}$$

$$V_{DS0,min} = V_{B0} - V_{TH0}$$

$$= \sqrt{\frac{2I_{SS}}{\mu_n C_{ox}(W/L)_0}}$$



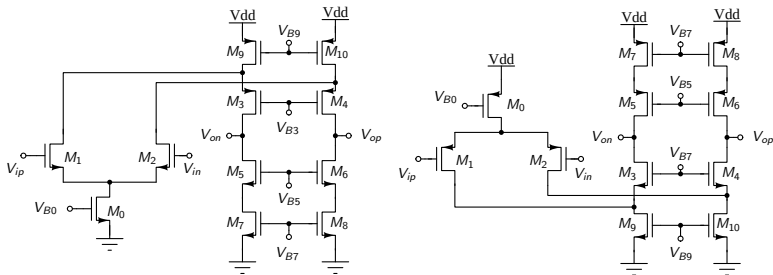
Output swing:

$$V_{IC,min} = V_{GS1,min} + V_{DS0,min}$$

$$V_{IC} - V_{TH1} < V_{B3} - V_{GS3} \Rightarrow V_{IC,max} = V_{B3} - V_{GS3} + V_{TH1}$$

very small range $\rightarrow$ $V_{B0} + V_{OV1} < V_{IC} < V_{B3} - V_{OV3}$ $\leftarrow$ assuming equal thresholds

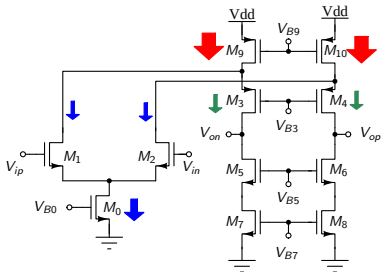
Fully-differential folded cascode amplifier



$$|A_{dm}| \approx g_{m1}(g_{m3}r_{ds3}(r_{ds9}||r_{ds1})||g_{m5}r_{ds5}r_{ds7})$$

$$|A_{cm}| \approx g_{m1}(g_{m3}r_{ds3}(r_{ds9})||g_{m5}r_{ds5}r_{ds7})/(1 + 2g_{m1}r_{ds0})$$

Fully-differential folded cascode amplifier

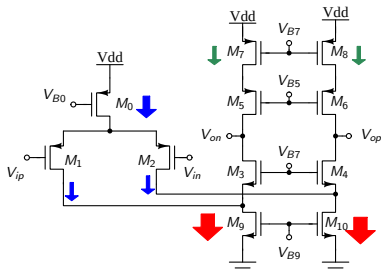


$$V_{IC,min} = V_{GS1} + V_{DS0,min}$$

$$V_{IC,max} = V_{dd} - V_{DS9,min} + V_{TH1}$$



$V_{IC,max}$ can be $\geq V_{dd}$



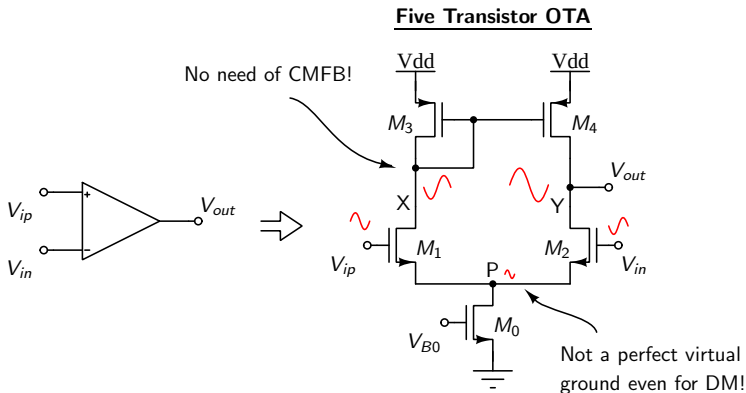
$$V_{IC,max} = V_{dd} - V_{DS0,min} - V_{SG1}$$

$$V_{IC,min} = V_{DS9,min} - |V_{TH1}|$$



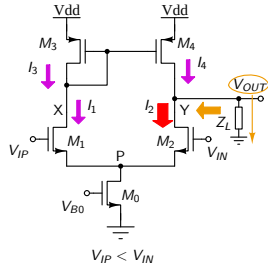
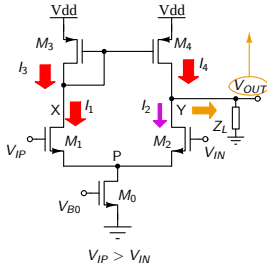
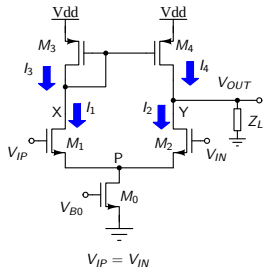
$V_{IC,min}$ can be ≤ 0

Differential to single-ended conversion



The circuit is not symmetric. $\Rightarrow$ We can't use equivalent half-circuits.

Large signal analysis of the OTA



When $V_{IP} = V_{IN}$,

$$V_X = V_Y = V_{dd} - |V_{GS3}|$$



Can be proved by contradiction

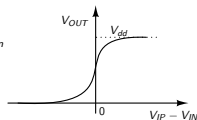
Input common-mode range:

For M_0 to be in saturation, $V_{IC} > V_{GS1} + V_{DS0,min}$

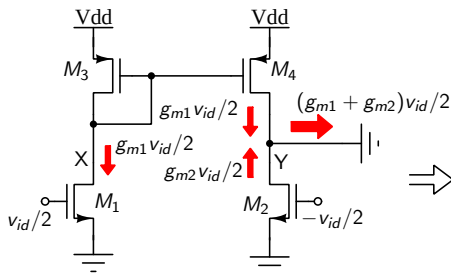
For M_1 to be in saturation, $V_X > V_{G1} - V_{TH1}$



$$V_{IC} < V_{dd} - |V_{GS3}| + V_{TH1}$$



Approximate differential-mode analysis of the OTA



Valid approximation if $r_{ds1,2}$ are high.

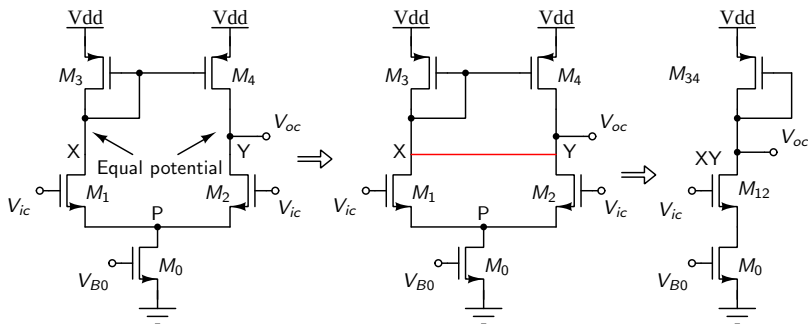
$$G_m \approx (g_{m1} + g_{m2})/2 \approx g_{m1}$$

$$Z_{out} \approx r_{ds2} || r_{ds4}$$



$$|A_{dm}| \approx g_{m1}(r_{ds2} || r_{ds4})$$

Approximate common-mode analysis of the OTA



$$|A_{cm}| \approx (g_{m1}/g_{m3})/(1 + 2g_{m1}r_{ds0})$$

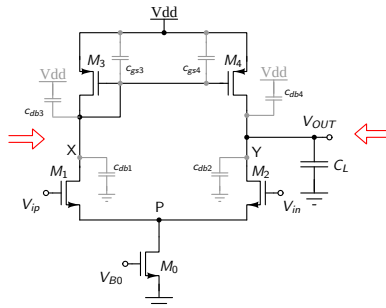
$$CMRR = \frac{|A_{dm}|}{|A_{cm}|} \approx (1 + 2g_{m1}r_{ds0})g_{m3}(r_{ds2} || r_{ds4})$$

Frequency response - 1

$$R_2 \approx 1/g_{m3}$$

$$C_2 \approx c_{gs3} + c_{gs4} + c_{db1} + c_{db3}$$

$$\omega_{p2} \approx 1/(R_2 C_2)$$



$$R_1 \approx r_{ds2} || r_{ds4}$$

$$C_1 \approx C_L + c_{db2} + c_{db4}$$

$$\omega_{p1} \approx 1/(R_1 C_1)$$

Neglected the c_{gd} of all transistors.

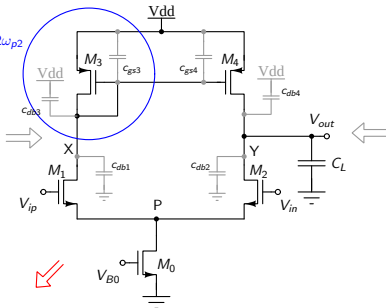
Frequency response - 2

Introduces a LH zero at $2\omega_{p2}$

$$R_2 \approx 1/g_{m3}$$

$$C_2 \approx c_{gs3} + c_{gs4} + c_{db1} + c_{db3}$$

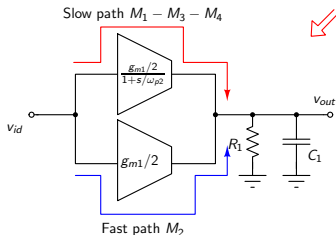
$$\omega_{p2} \approx 1/(R_2 C_2)$$



$$R_1 \approx r_{ds2} || r_{ds4}$$

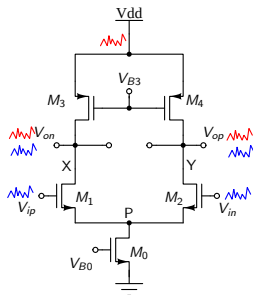
$$C_1 \approx C_L + c_{db2} + c_{db4}$$

$$\omega_{p1} \approx 1/(R_1 C_1)$$



$$\begin{aligned} |A_d| &= \frac{g_{m1} R_1 / 2}{1 + s/\omega_{p1}} + \frac{g_{m1} R_1 / 2}{(1 + s/\omega_{p1})(1 + s/\omega_{p2})} \\ &= \frac{g_{m1} R_1 / 2}{(1 + s/\omega_{p1})} \left[1 + \frac{1}{1 + s/\omega_{p2}} \right] \\ &= \frac{(g_{m1} R_1 / 2)(2 + s/\omega_{p2})}{(1 + s/\omega_{p1})(1 + s/\omega_{p2})} \end{aligned}$$

Comparison of FDA and OTA

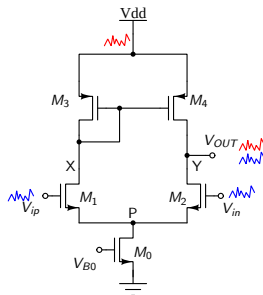


FDA

No parasitic poles in the differential response

No change in the differential output for changes in the supply and CM input.

Need CMFB loop for a stable bias.



OTA

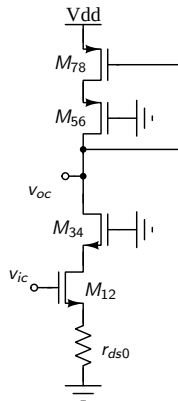
One mirror pole in the differential response

Output changes with supply and CM noise.

No need of CMFB loop.

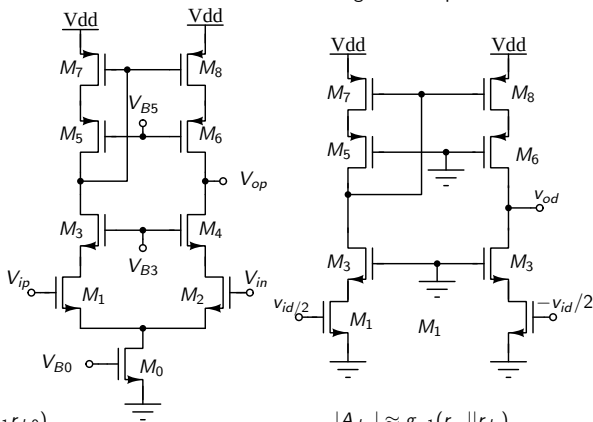
Telescopic cascode with single-ended output

Small-signal CM equivalent



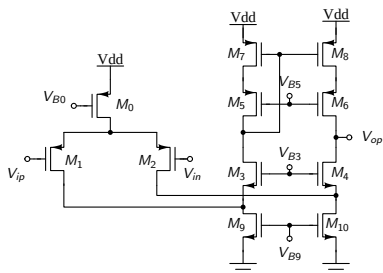
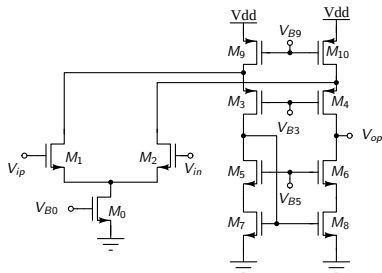
$$|A_{cm}| \approx (g_{m1}/g_{m7})/(1 + 2g_{m1}r_{ds0})$$

Small-signal DM equivalent



$$|A_{dm}| \approx g_{m1}(r_{up}||r_{dn})$$

Folded cascode with single-ended output



$$|A_{dm}| \approx g_{m1}(g_{m4}r_{ds4}r_{ds10} || g_{m6}r_{ds6}r_{ds8})$$

$$|A_{cm}| \approx (g_{m1}/g_{m7})/(1 + 2g_{m1}r_{ds0})$$

Summary

- ▶ Current sources/sinks can be used as load elements to achieve high gain
- ▶ Fully-differential amplifiers need a common-mode stabilization circuit
- ▶ Telescopic and folded cascode amplifiers can provide high gain but there is no improvement in CMRR
- ▶ Current mirrors can also be used as load elements
- ▶ Differential amplifiers with single-ended outputs suffer from mirror poles
- ▶ Folded cascode amplifiers can support input common-mode voltages upto/beyond one-end of the supply