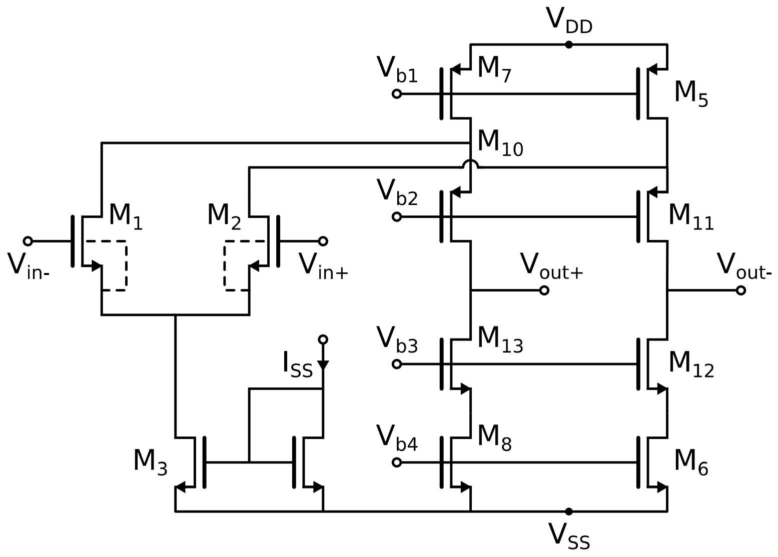
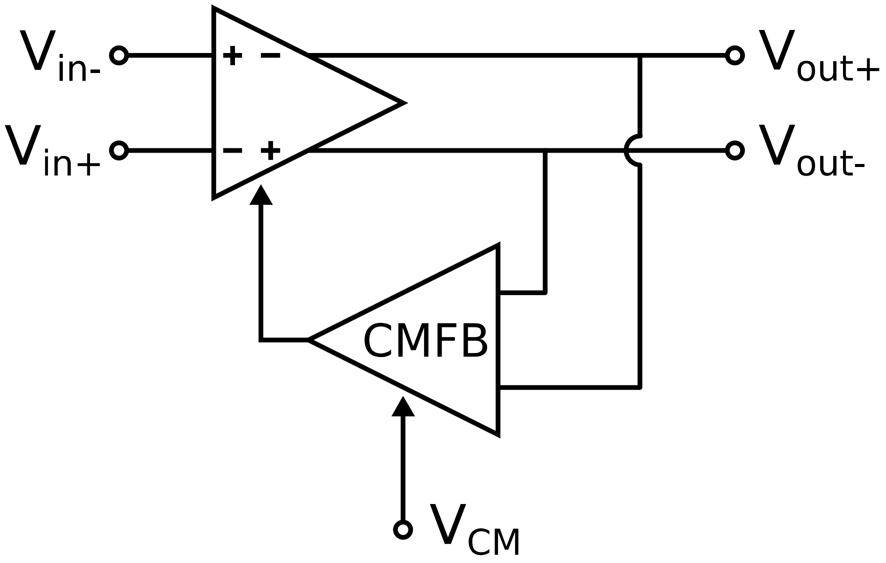
ELEC-E3510 Basics of IC Design

Lecture 7:
Common-mode feedback

Common-mode feedback

Common-mode amplifier is needed in fully-differential amplifier to stabilize the output DC-levels.
Output common-mode level is tuned by tuning the biasing currents of the amplifier
(either in the input stage or in the output stage).

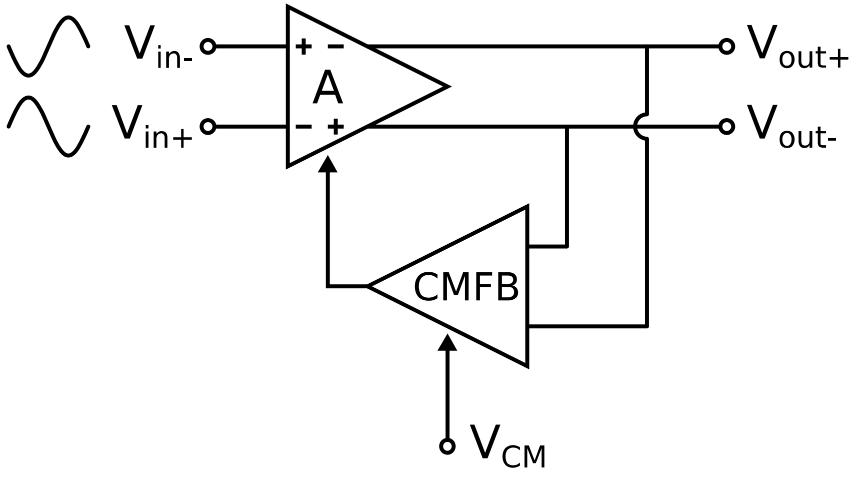


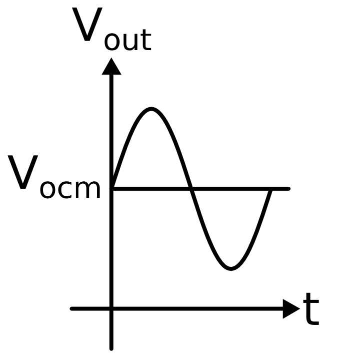


CMFB: common-mode feedback amplifier (error amplifier)
V_{CM}: external common-mode voltage

Common-mode feedback

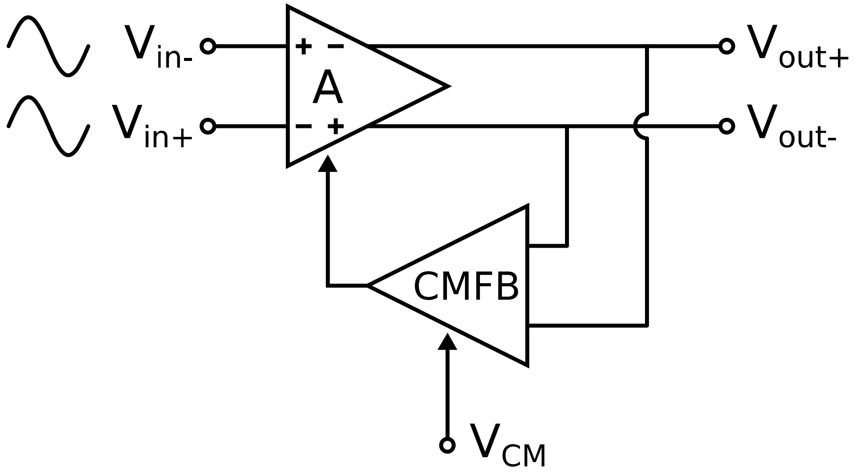
Differential input signal:

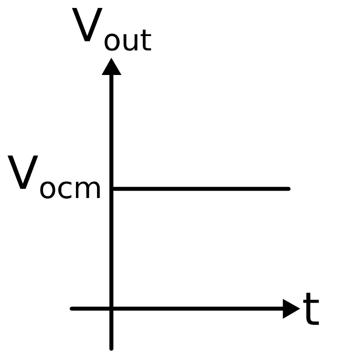




Common-mode feedback does not affect the differential signal.

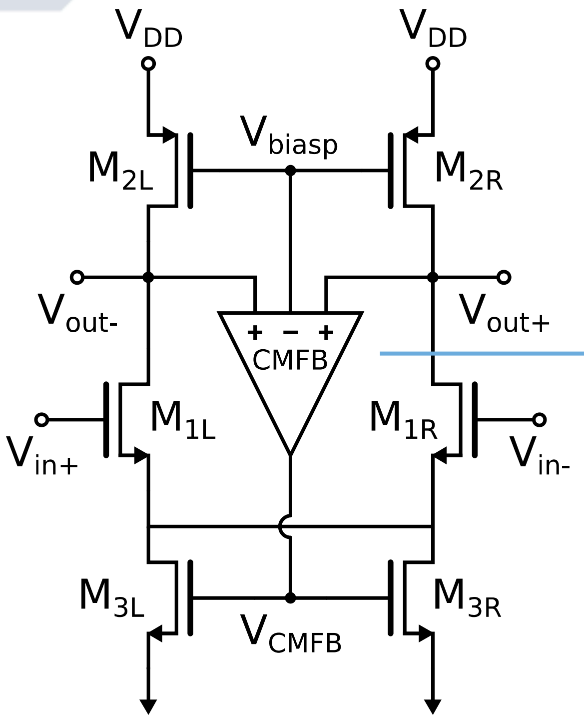
Common-mode input signal:



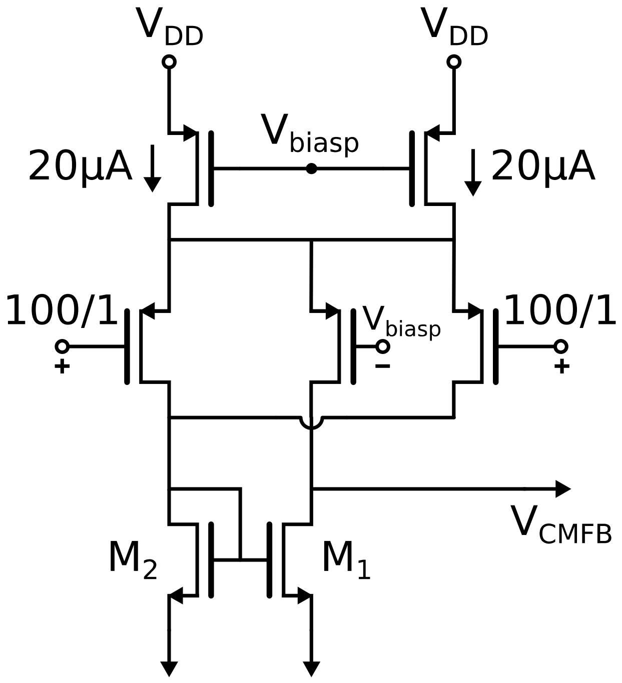


Common-mode output voltage V_{ocm} midway between the limits of the signal swing (normally power-supply voltages)

Using a CMFB amplifier to set output voltages



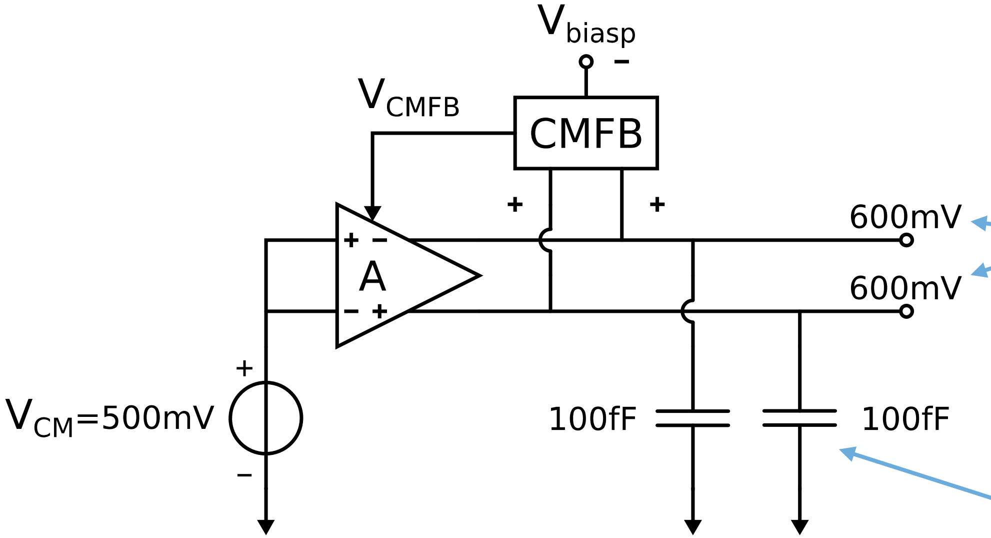
One possible implementation of CMFB amplifier



- CMFB amplifier is used to amplify the difference between the average of the differential amplifiers outputs and V_{biasp}.
- If the gain of the CMFB is large, the average of the two outputs will be very close to V_{biasp}.
- Any variation in V_{CMFB} affects each output by the same amount.
- CMFB amplifier shouldn't affect the differential amplification in the differential amplifier.
- When the differential amplifier outputs are equal, they should be V_{biasp}.

Operation of the CMFB circuit

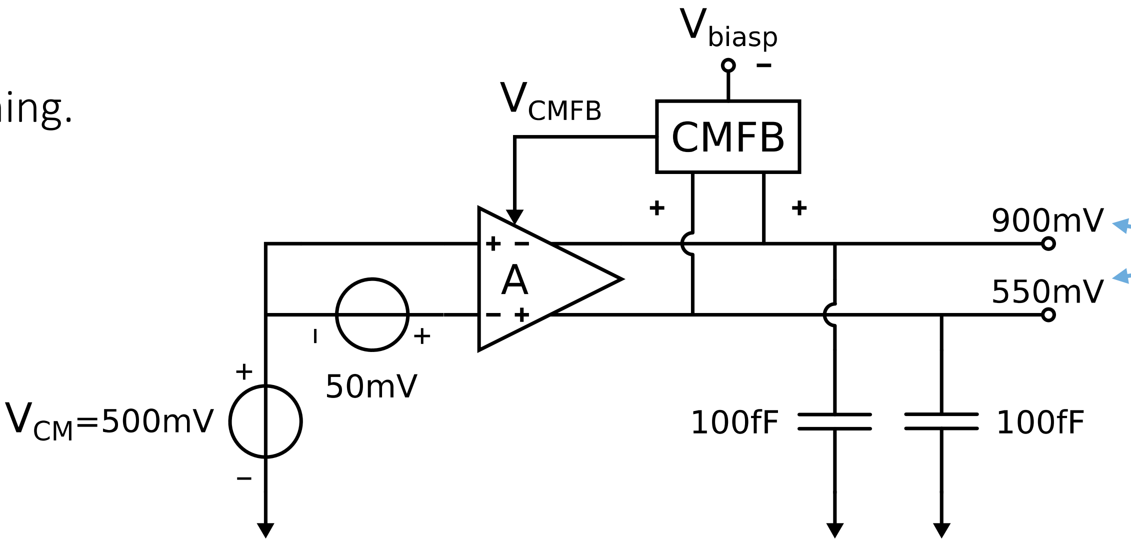
a) No offset



Correct outputs, i.e. V_{biasp}

Needed to stabilize the CMFB loop

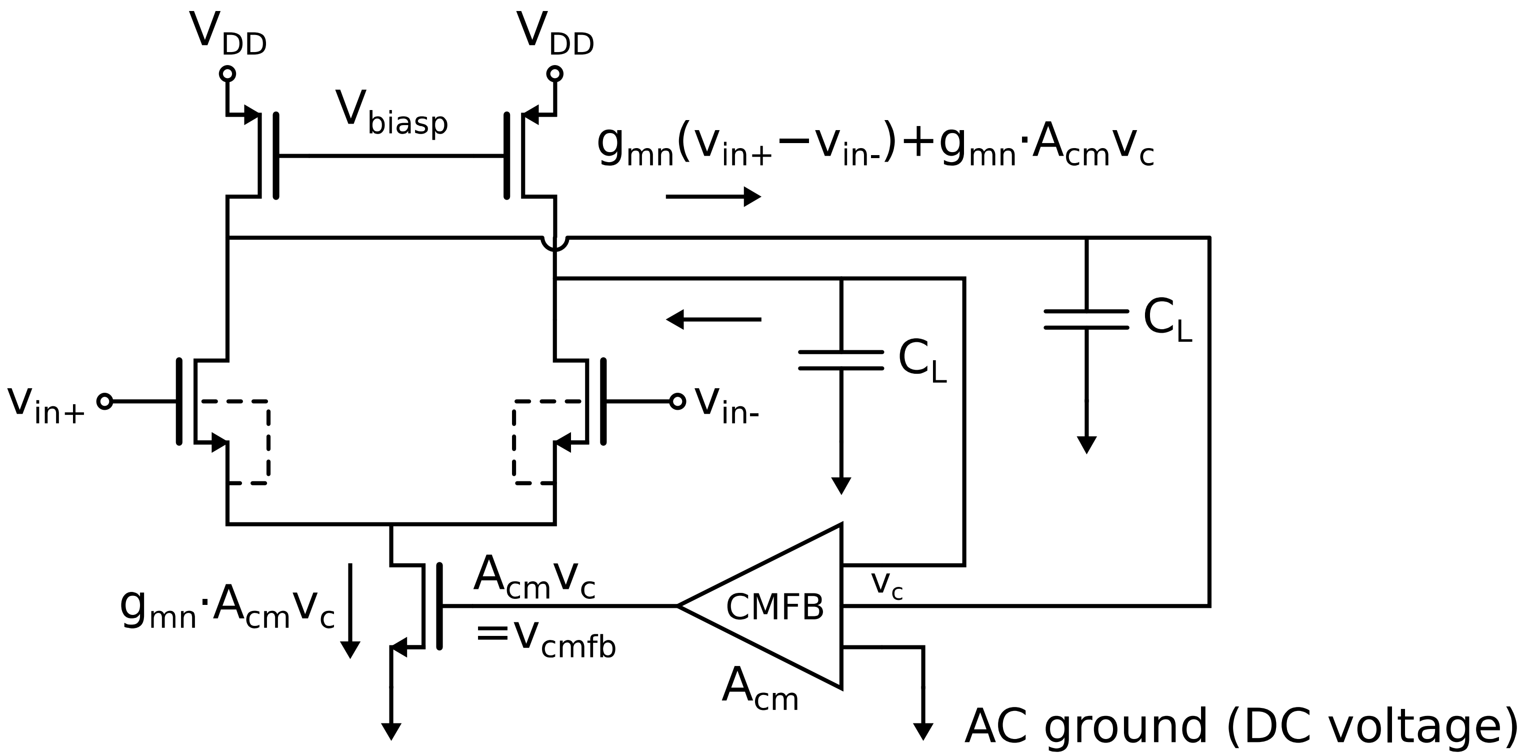
b) With a 50mV offset:
Note how the CMFB isn’t doing anything.



Outputs not balanced

⇒ We must use a CMFB that can balance the output over the entire range of diff-amp output voltage.

Compensating the CMFB loop



- v_C is the AC common-mode signal
- Unity gain frequency of CMFB loop is

$$f_{un,cm} = \frac{A_{cm} \cdot g_{mn}}{2\pi \cdot C_L}$$

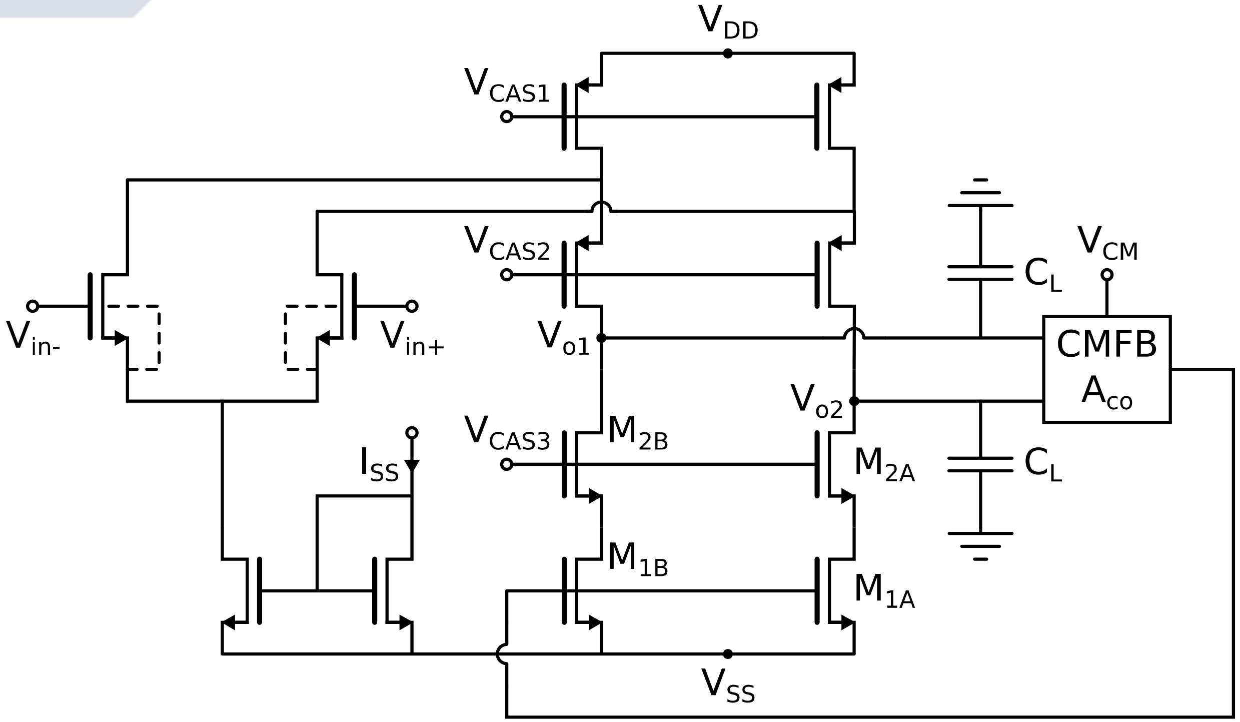
- If we want to compensate the CMFB loop with the same load capacitance used to compensate the differential forward signal path, then we must ensure that the gain of the CMFB amplifier is

$$A_{cm} \leq 1$$

CMFB design essentials

- CMFB is only to adjust DC levels, not for signal quality
- Should not limit the speed of the amplifier
- Must be stable
- Should not limit the signal swing
- Common-mode range as large as possible
- No differential to common-mode conversion
- No common-mode to differential conversion
- Must be functional over all signal conditions
- As simple as possible (only DC level adjustment)
- Low power
- Not accurate (even 100mV error can be tolerable in many cases)

Common-mode feedback loop



- Gain of common-mode feedback loop:

$$A_{LOOP} = -A_{CO}\frac{g_{m1}g_{m2}}{g_{DS1}g_{DS2}} \approx \frac{10^{-3}10^{-3}}{10^{-6}10^{-6}} = 10^{6}$$

- Output resistance of common-mode circuit:

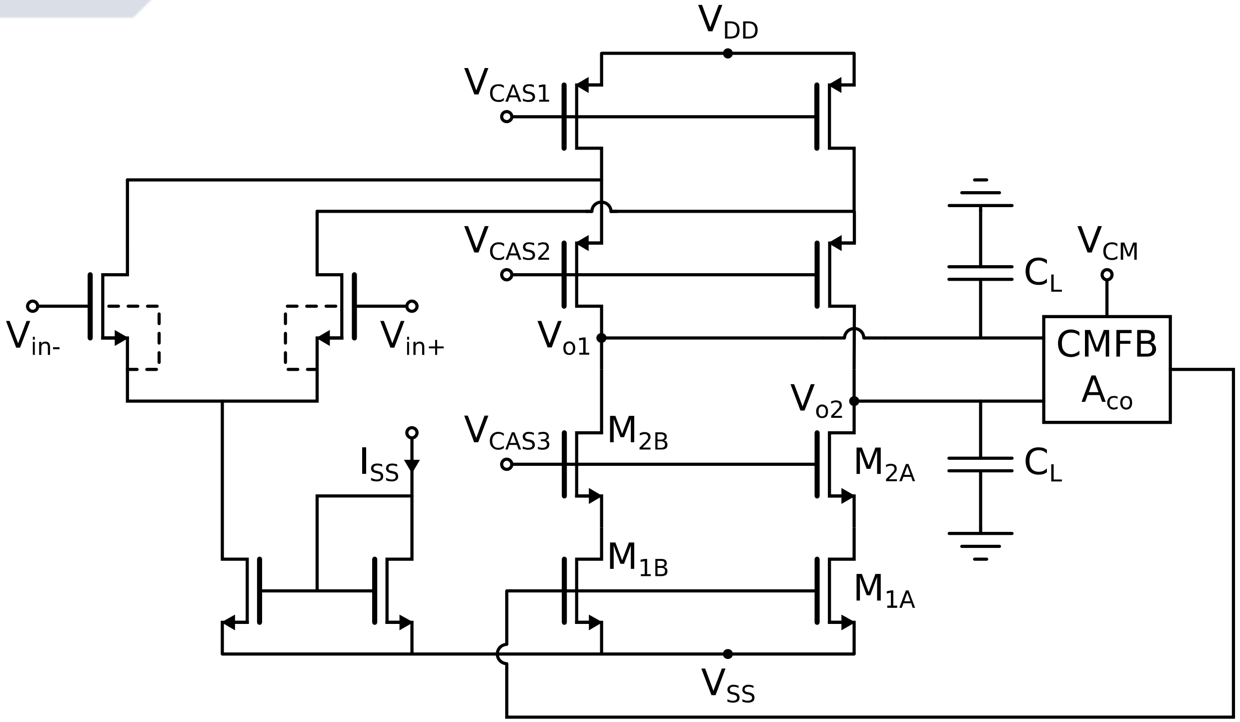
$$R_{o,CM} = \frac{1}{A_{CO}g_{m1}}$$

- If M_{1A} and M_{1B} are fully matched, only common-mode signal is fed back
- If M_{1A} and M_{1B} are fully matched, also differential signal will be fed back $\Rightarrow A_{dM}\downarrow$

$$\Delta A_{diff} = -A_{CO}\frac{g_{m1}g_{m2}}{g_{DS1}g_{DS2}}\left[2\frac{\Delta g_{DS1}}{g_{DS1}} + 2\frac{\Delta g_{m1}}{g_{m1}}\right]$$

$$\left.\begin{array}{l}\Delta g_m \sim \Delta L \\ \Delta g_{DS1} \sim \dfrac{1}{\Delta L}\end{array}\right\} \Rightarrow \text{ca. 1\% error}$$

Common-mode feedback loop

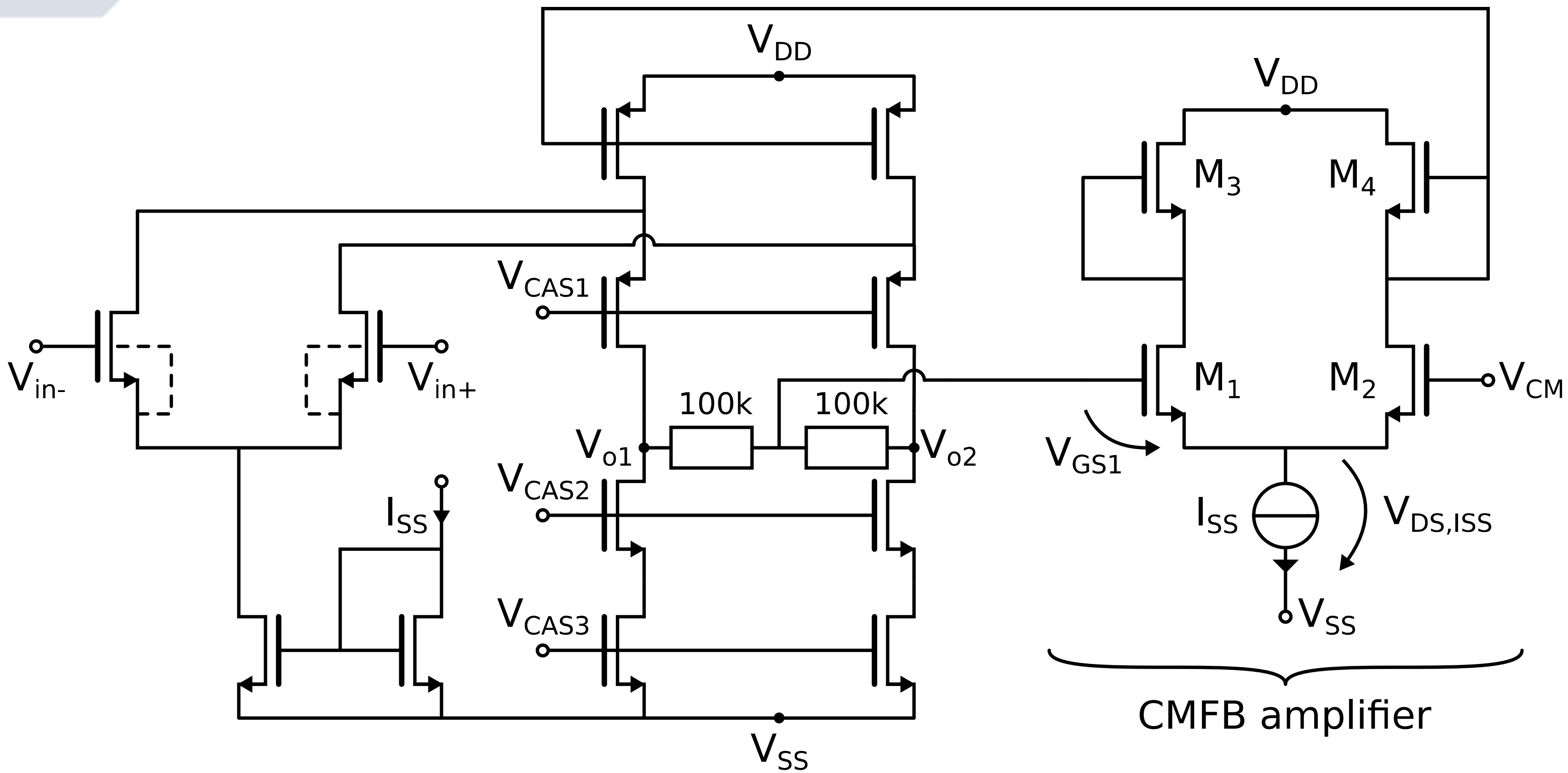


- Pole of common-mode feedback loop:

$$p_{CMFB} = \frac{A_{CO} g_{m1}}{C_L}$$

- Typically p_{CMFB} limits common-mode feedback loop
  $\Rightarrow A_{CO}\uparrow$ or $g_{m1}\uparrow$

Common-mode detection with resistors



- CMFB amplifier compares with an external CM-level
- Gain of CMFB amplifier:

$$A_{CO} = \frac{g_{m1}}{g_{m4}} > 1$$

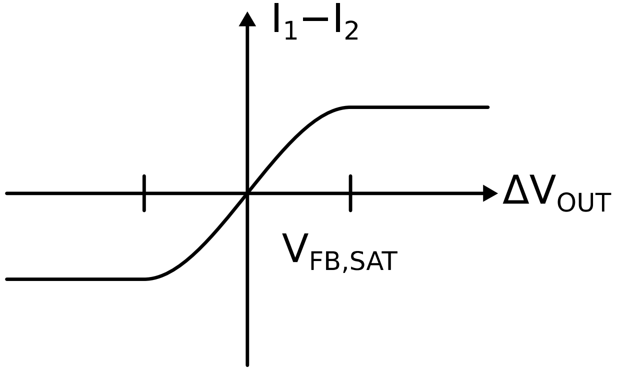
Limited common-mode range

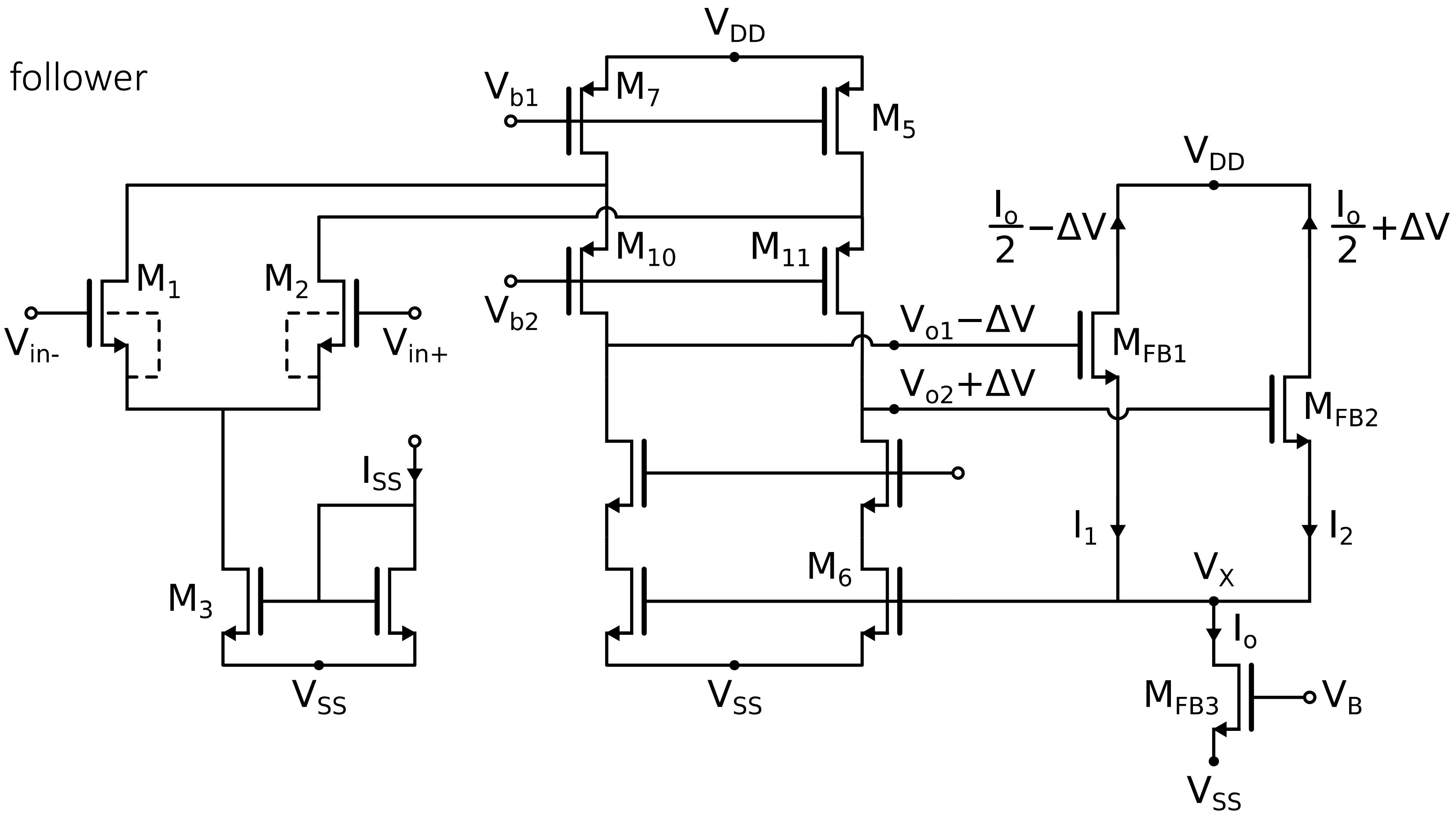
$Min\{V_{CM}\} = V_{GS1} + V_{DS,ISS}$

$R_{CM} >> R_{OUT} > 1M\Omega$

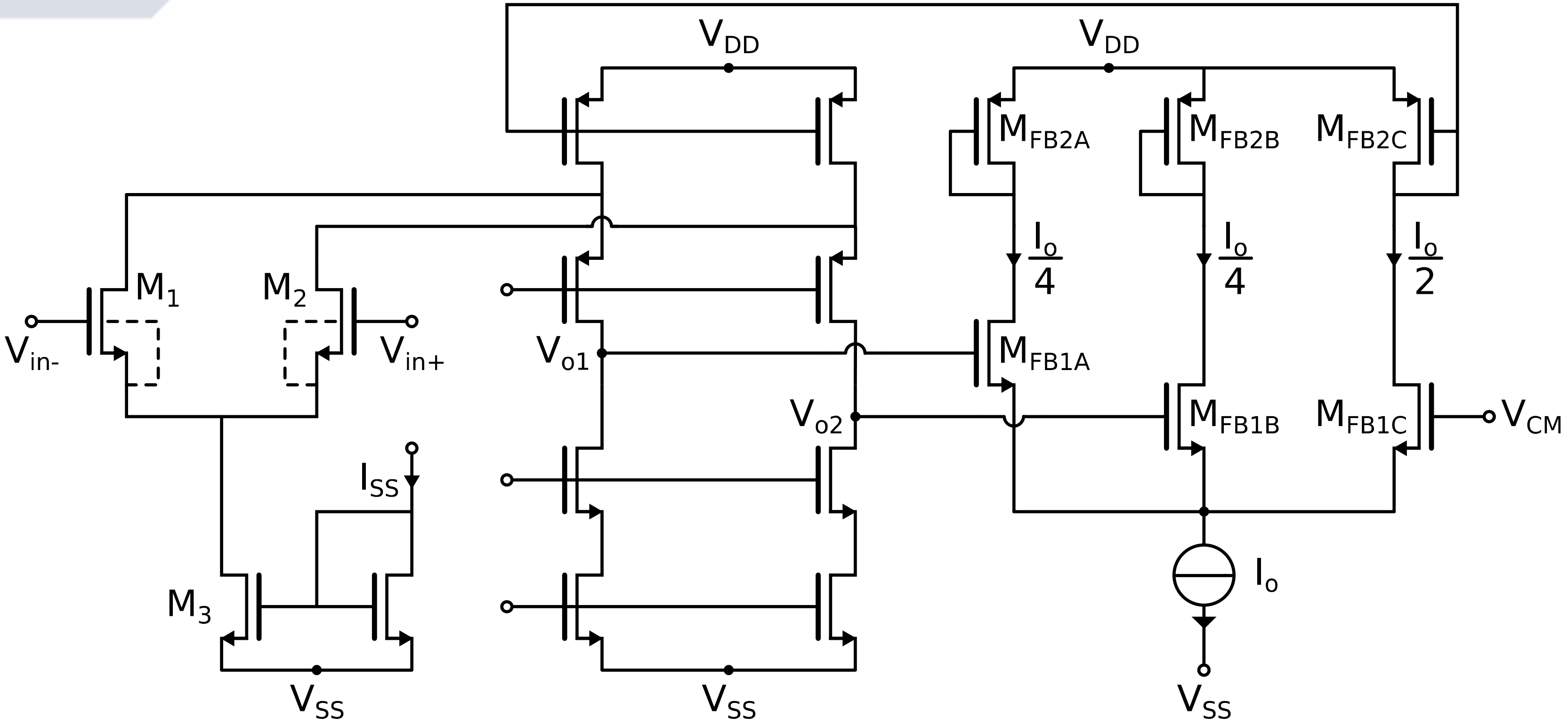
Common-mode detection with transistors only

- Common-mode feedback with source follower
  $A_{CM} = 1$
- Limited common-mode range
  $\min\{CM\} = V_{GS,FB1} + V_{GS6}$
  $\max\{CM\} = V_{DD}$
- Limited differential signal range
  $\max\{\Delta V_{OUT}\} < V_{FB,SAT} = \sqrt{2}\, V_{SAT,FB1}$
- V_X depends on ΔV_{OUT}
  $\Rightarrow \Delta v_{diff} \longrightarrow \Delta V_{CM}$ transformation!





CMFB with double differential amplifier



- Common-mode detection with source-coupled pair M_{FB1A} and M_{FB1B}
- Common-mode comparison and feedback with source-coupled pair formed by M_{FB1A}+M_{FB1B} and M_{FB1C}

$$\Rightarrow \left(\frac{W}{L}\right)_{MFB1A,MFB1B} = \frac{1}{2}\left(\frac{W}{L}\right)_{MFB1C}$$

- Gain and pole of CMFB:

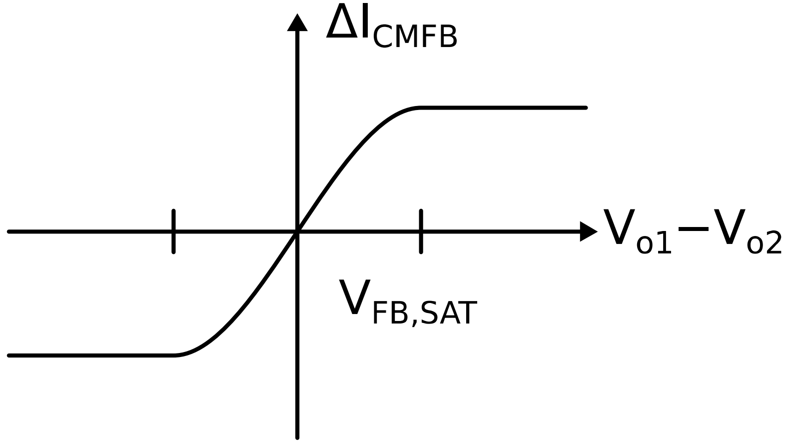
$$A_{CO} = \frac{g_{m,MFB1C}}{g_{m,MFB2C}}$$

$$\text{pole} = \frac{g_{m,MFB2}}{C_{GS,MFB2}}$$

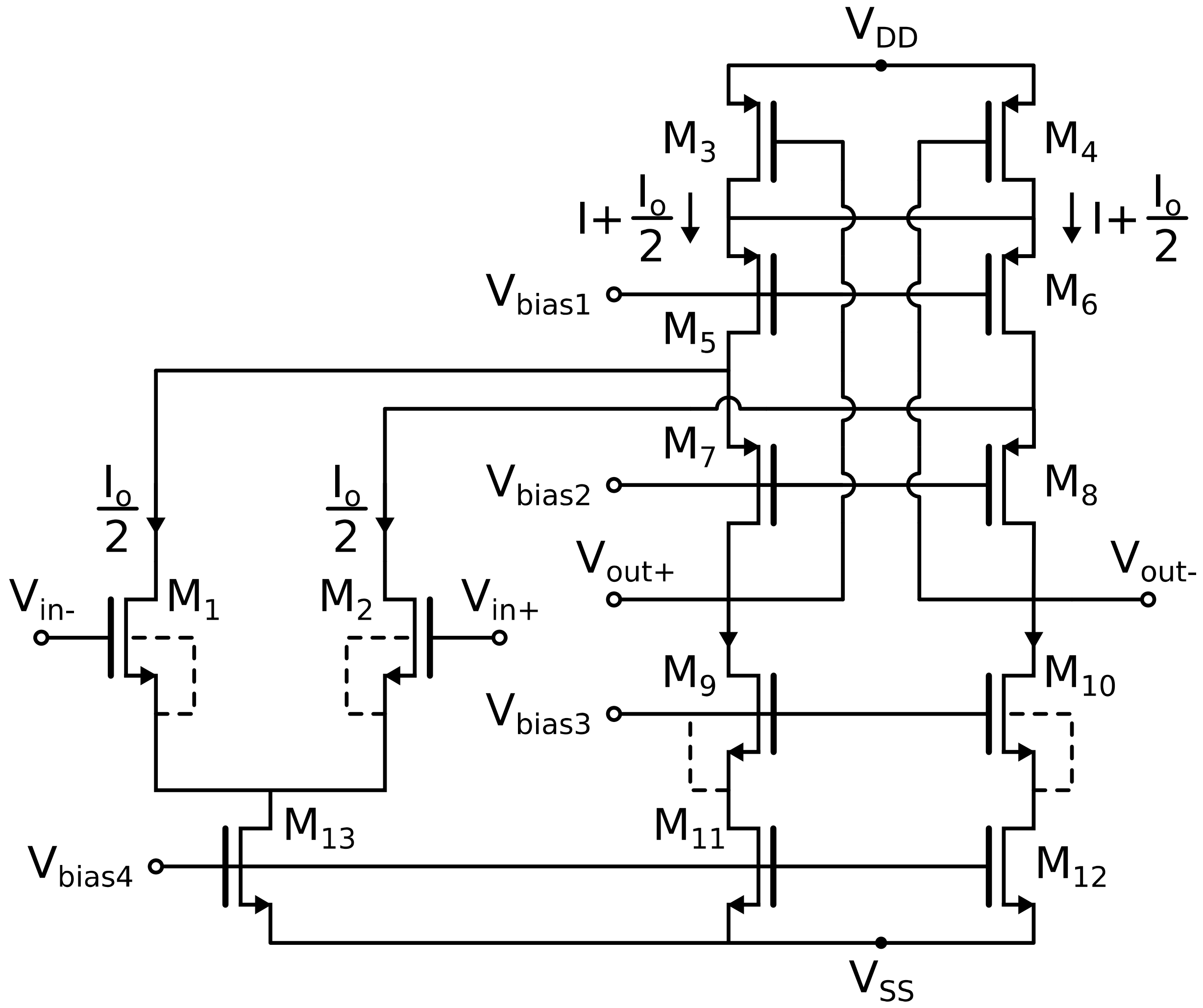
Fast common-mode settling

- Limited common-mode range

- Limited differential output swing, if $|V_{o1} - V_{o2}| > V_{FB,SAT}$
  $\rightarrow A_{CO} \rightarrow$ no common-mode feedback!



Source degeneration common-mode feedback loop



- Common-mode feedback is performed by M_3 and M_4
- M_3 and M_4 work as source degeneration resistors controlled by output common-mode voltage
- M_3 and M_4 in linear region i.e. parallel conductance is

$$g_{CM} = g_{DS3} + g_{DS4}$$

$$g_{DS3} = \mu C_{OX} \frac{W}{L}\left(V_{DD} - V_{OUT+} - V_T\right)$$

$$g_{DS4} = \mu C_{OX} \frac{W}{L}\left(V_{DD} - V_{OUT-} - V_T\right)$$

ass. $V_{OUT+} = V_o + \Delta V,\ \ V_{OUT-} = V_o - \Delta V$

$$\Rightarrow \quad g_{CM} = \mu C_{OX} \frac{W}{L}\left(V_{DD} - V_o - \Delta V - V_T + V_{DD} - V_o + \Delta V - V_T\right)$$

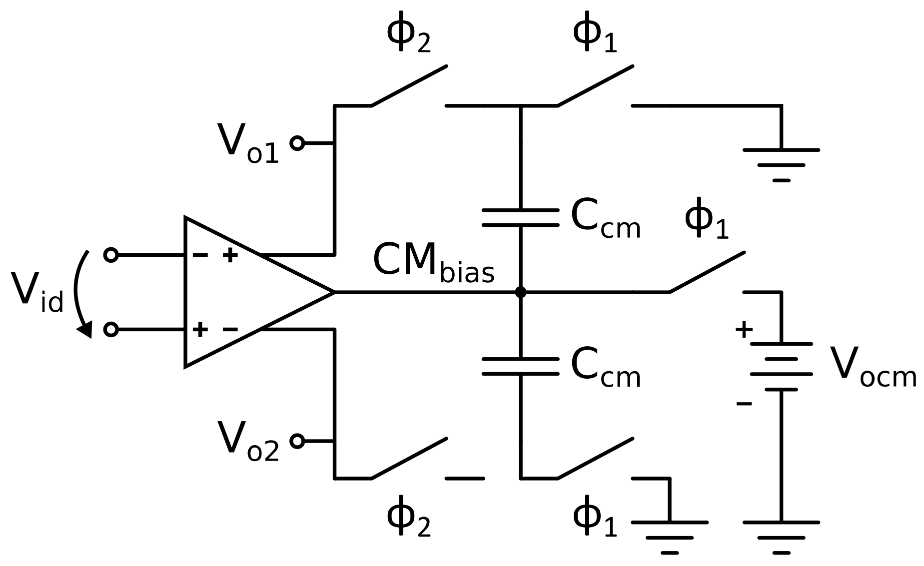
$$= 2\mu\mu_{OX} \frac{W}{L}\left(V_{DD} - V_o - V_T\right)$$

- Gain of common-mode feedback:

$$A_{CO} = \frac{g_{m3}}{g_{DS3}} < 1 \quad ; V_{DS3} < V_{DS,SAT}$$

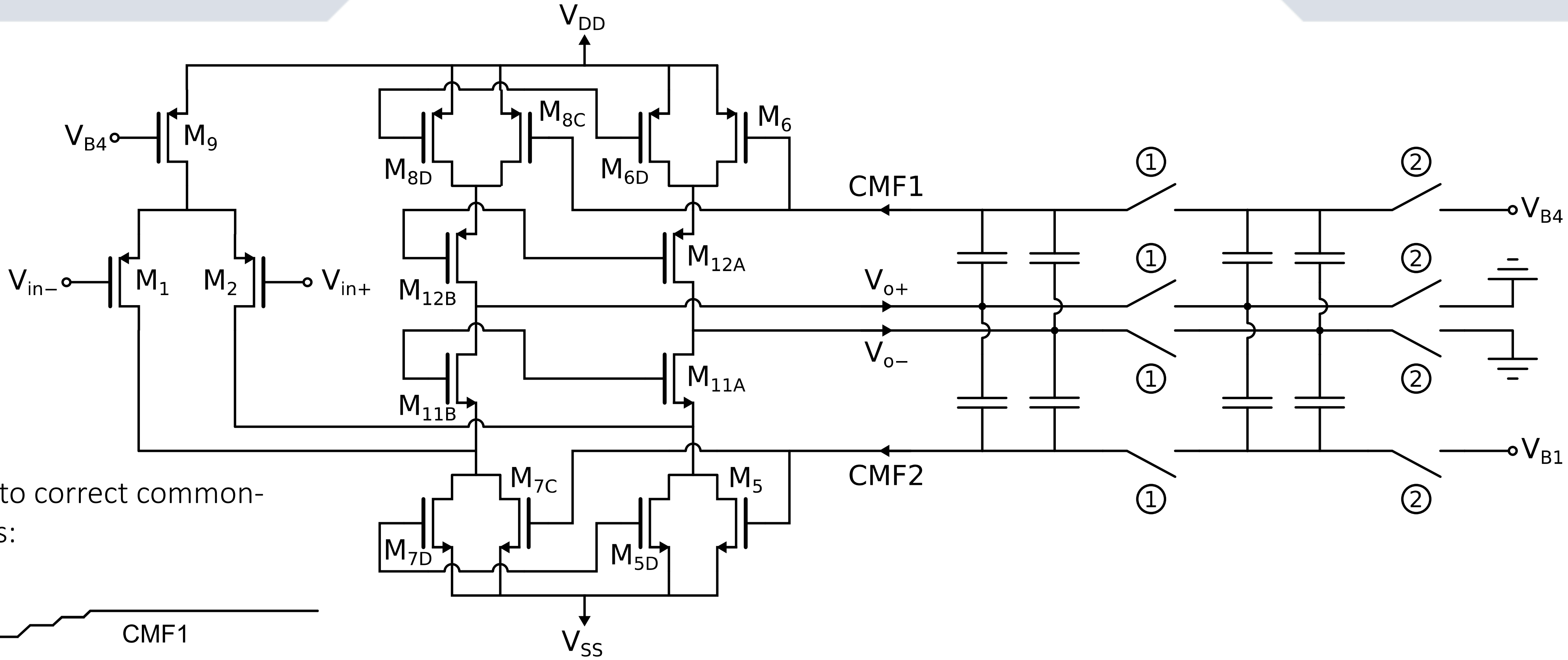
$\Rightarrow$ slow!

SC common-mode feedback

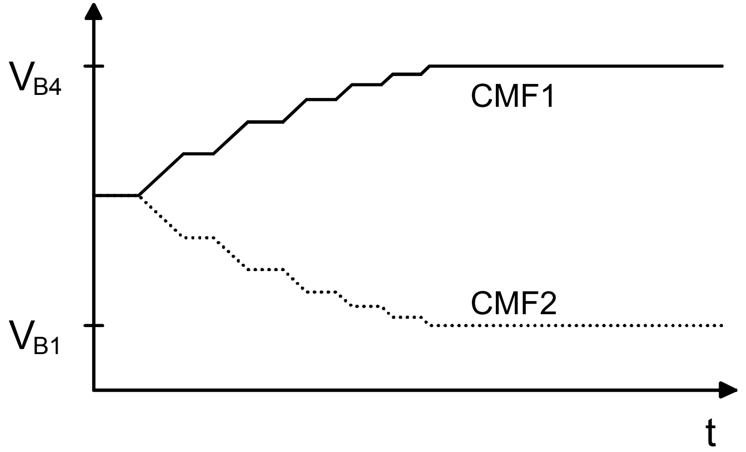


- Op-amp is used only during the ϕ_2 phase
- Cm_{bias} is an input that determines common-mode output voltage
- Phase ϕ_1: both capacitors C_{cm} are charged to the desired value of output voltage V_{ocm}
- Phase ϕ_2: both capacitors C_{cm} (charged to V_{ocm}) are connected between the differential output nodes and Cm_{bias}
- The average voltage applied to Cm_{bias} node will be V_{ocm}
- The voltage across C_{cm} does not change when phase periods are small enough

SC common-mode feedback

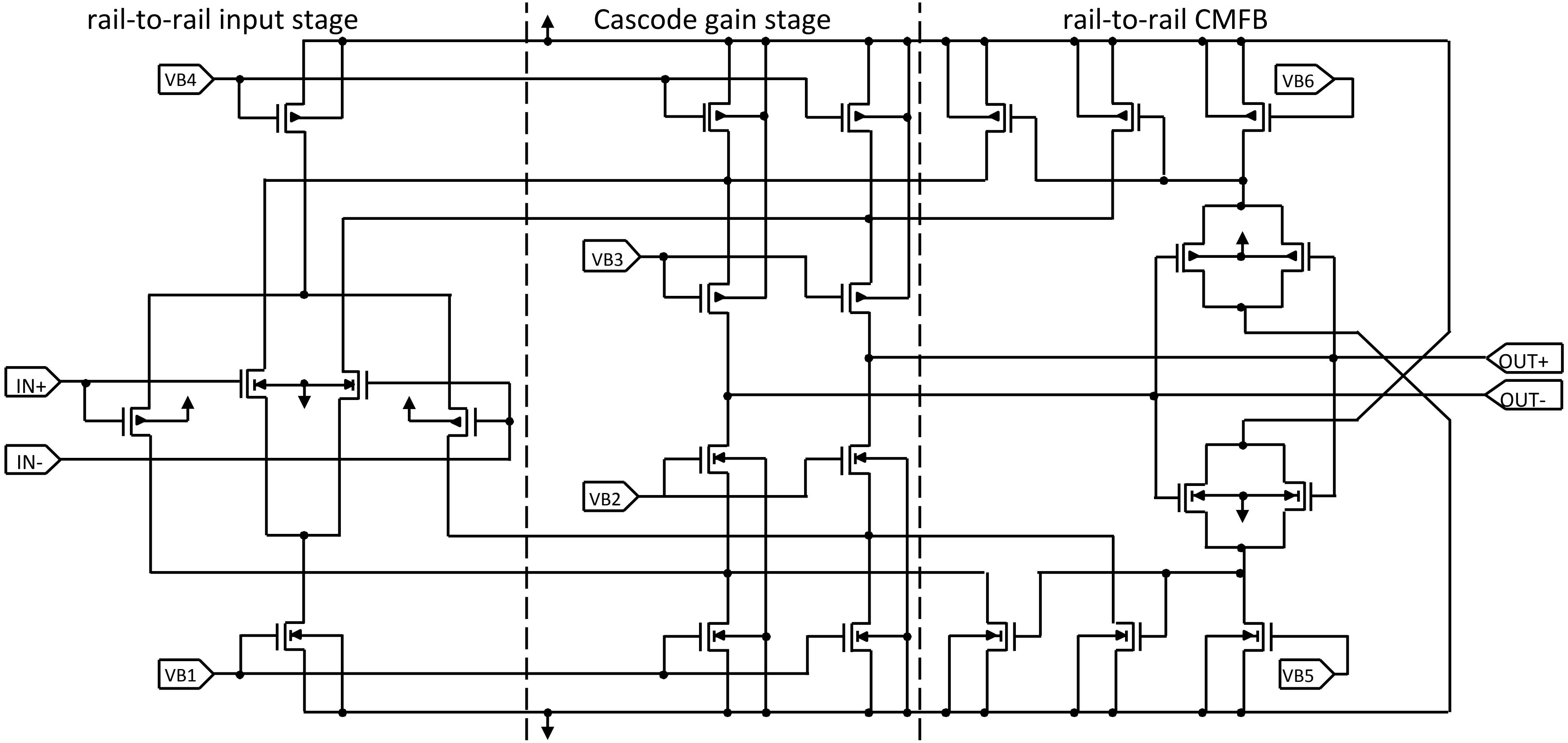


Start-up settling to correct common-mode bias values:



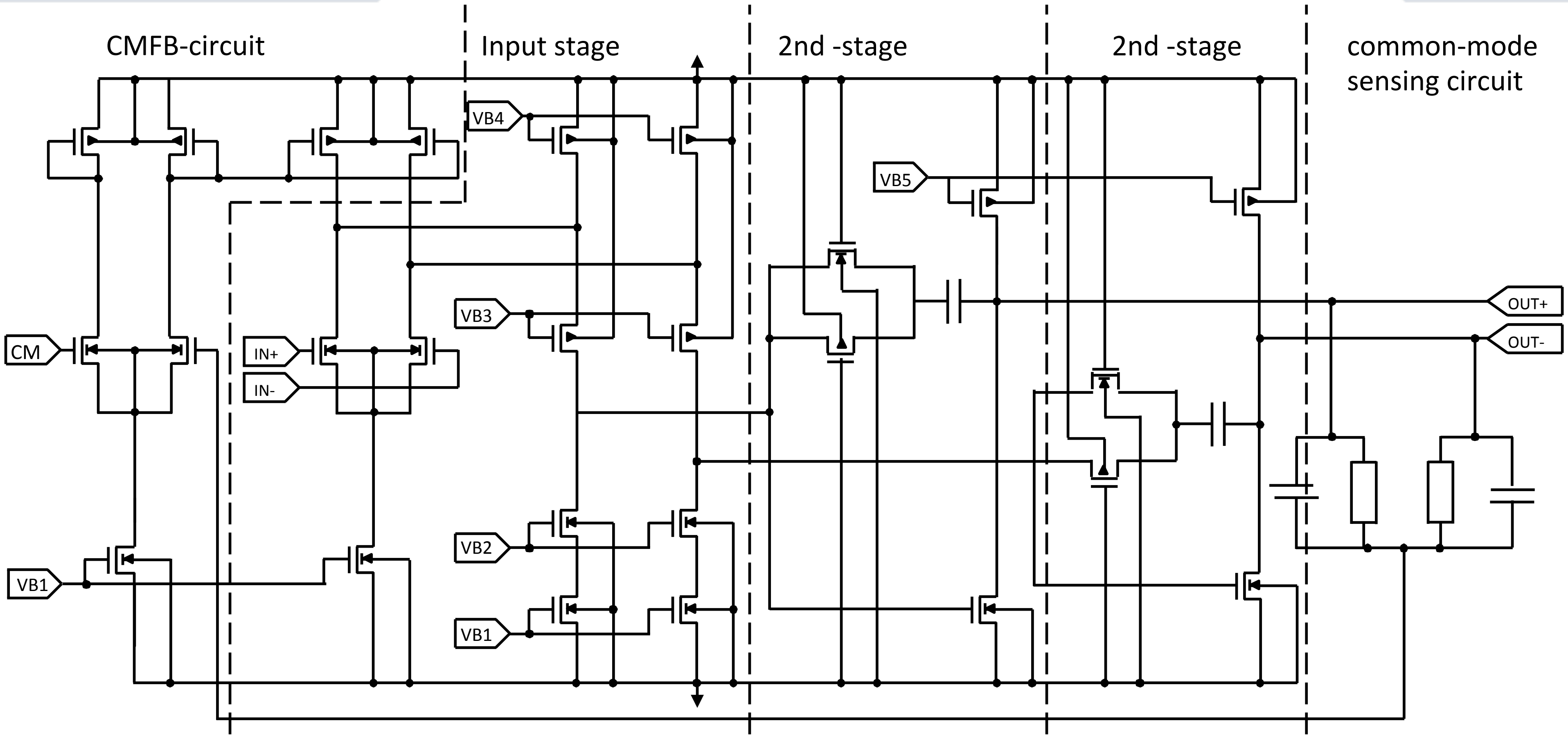
- Fast settling to new common-mode level i.e. only charge sharing between capacitors
- Switched capacitors to refresh transistor bias voltages

Folded cascode OTA with rail-to-rail common-mode levels



- NMOS and PMOS input stages in parallel
  ⇒ rail-to-rail input common-mode range
- NMOS and PMOS common-mode feedback circuits
  ⇒ rail-to-rail common-mode detection range

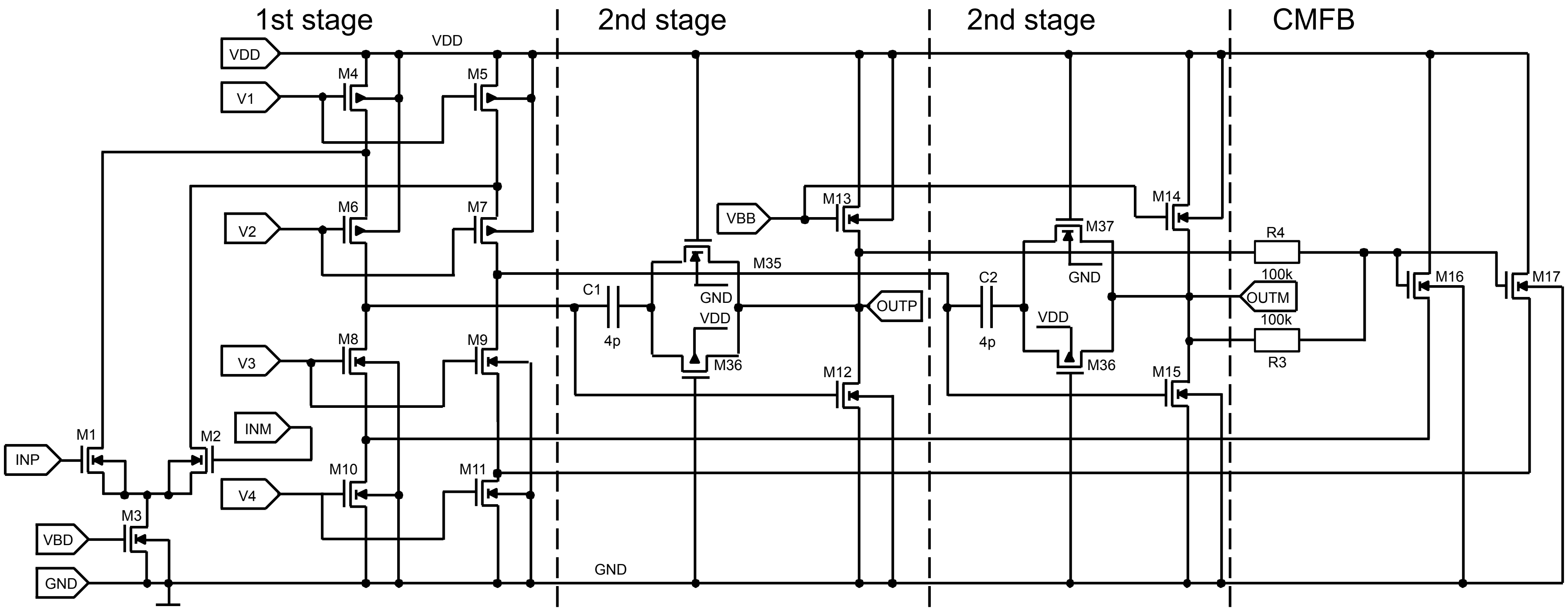
Fully differential Miller compensated two stage amplifier



- Folded cascode input stage
- Miller compensated 2nd stage
- Common-mode sensing with resistors
- Common-mode feedback with differential amplifier

- Limited common-mode range
- Stability – speed trade-off

Fully differential Miller compensated two stage amplifier



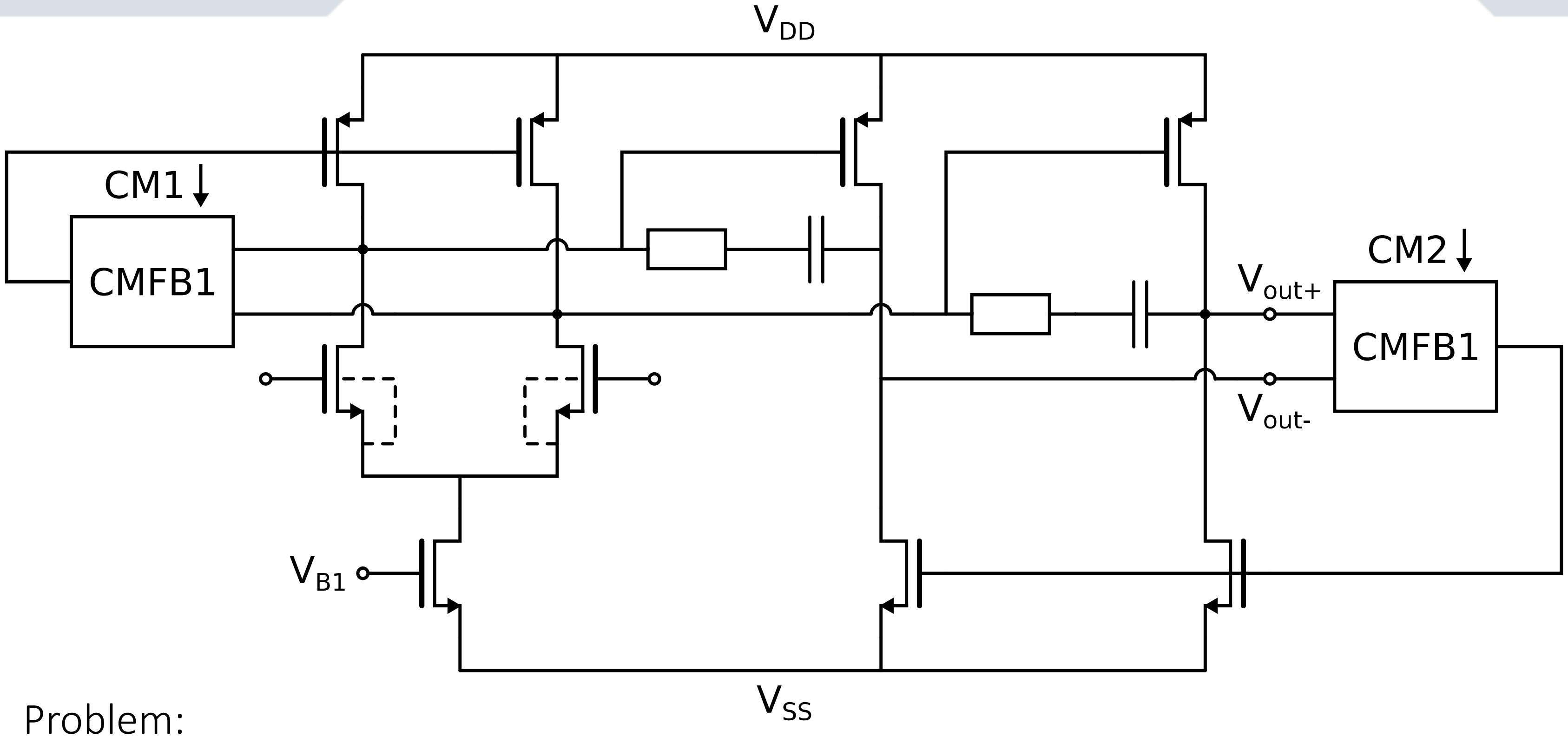
- Folded cascode 1st stage
- Miller compensated 2nd stage
- Current steering common-mode feedback
- Common-mode sensing with resistors

- Stability-speed trade-off in CMFB (CMFB over both amplifier stages)
- Limited common-mode range

  $\min\{CM\} = V_{GS16} + V_{DS10}$

  $= V_T + 2V_{DS,SAT}$

Fully differential 2-stage amplifier with double CMFB circuit



Problem:

- One global CMFB from the output to input stage is difficult to design fast enough
- Also stability might be a problem

Solution:

- Separate local CMFB circuits for the input stage and output stage

⇒ Increase complexity and power consumption