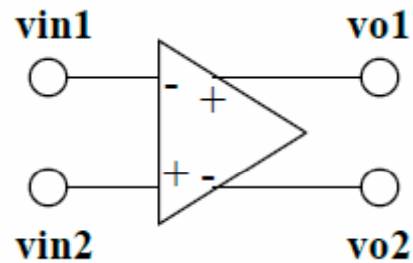


Fully Differential OTA

Fully-Differential Circuits



$$v_{o1} = \frac{v_{o1} - v_{o2}}{2} + \frac{v_{o1} + v_{o2}}{2} = \frac{v_{od}}{2} + v_{oc}$$

$$v_{o2} = \frac{v_{o2} - v_{o1}}{2} + \frac{v_{o1} + v_{o2}}{2} = -\frac{v_{od}}{2} + v_{oc}$$

$$\begin{bmatrix} v_{od} \\ v_{oc} \end{bmatrix} = \begin{bmatrix} A_{dd} & A_{dc} \\ A_{cd} & A_{cc} \end{bmatrix} \begin{bmatrix} v_{id} \\ v_{ic} \end{bmatrix}$$

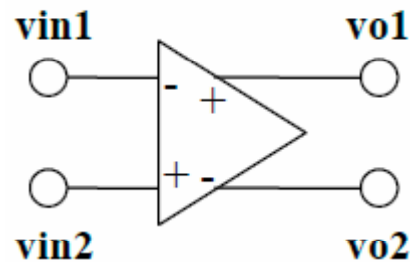
- Differential-mode output

$$A_{dd} = \left. \frac{v_{od}}{v_{id}} \right|_{v_{ic}=0} \quad A_{dc} = \left. \frac{v_{od}}{v_{ic}} \right|_{v_{id}=0}$$

- Common-mode output

$$A_{cd} = \left. \frac{v_{oc}}{v_{id}} \right|_{v_{ic}=0} \quad A_{cc} = \left. \frac{v_{oc}}{v_{ic}} \right|_{v_{id}=0}$$

Fully-Differential Filters: Effects of current source impedance and mismatches

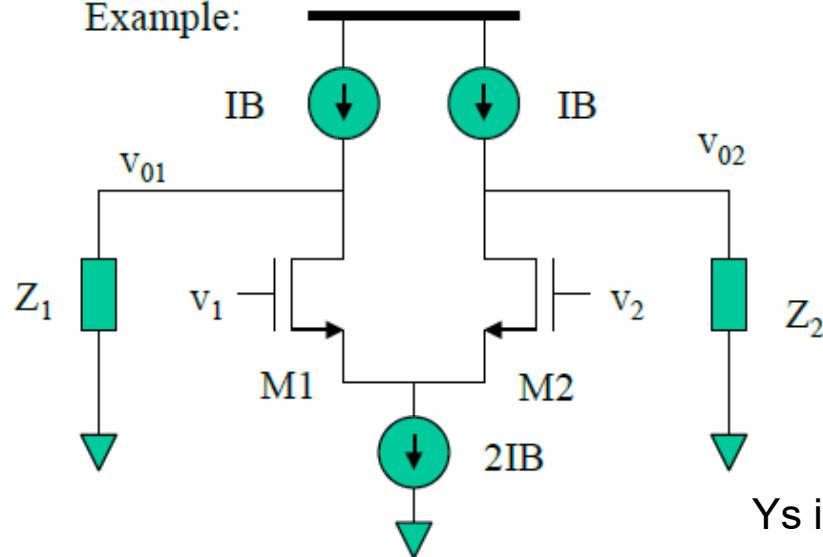


A very important parameter:

$$CMRR = \frac{A_{dd}}{A_{dc}}$$

$$v_{id} = v_{i2} - v_{i1} \quad v_{ic} = \frac{v_{i2} + v_{i1}}{2}$$

Example:



Solving the circuit:

$$v_{01} = \frac{g_{m1}g_{m2}Z_1}{g_{m1} + g_{m2} + Y_s} \left[\left(1 + \frac{Y_s}{2g_{m2}} \right) v_{id} - \left(\frac{Y_s}{g_{m2}} \right) v_{ic} \right]$$

$$v_{02} = \frac{g_{m1}g_{m2}Z_2}{g_{m1} + g_{m2} + Y_s} \left[- \left(1 + \frac{Y_s}{2g_{m1}} \right) v_{id} - \left(\frac{Y_s}{g_{m1}} \right) v_{ic} \right]$$

Y_s is the admittance associated with the current source $2IB$

- Voltage gain: Note the effects of the mismatches, especially in A_{dc} and A_{cd}

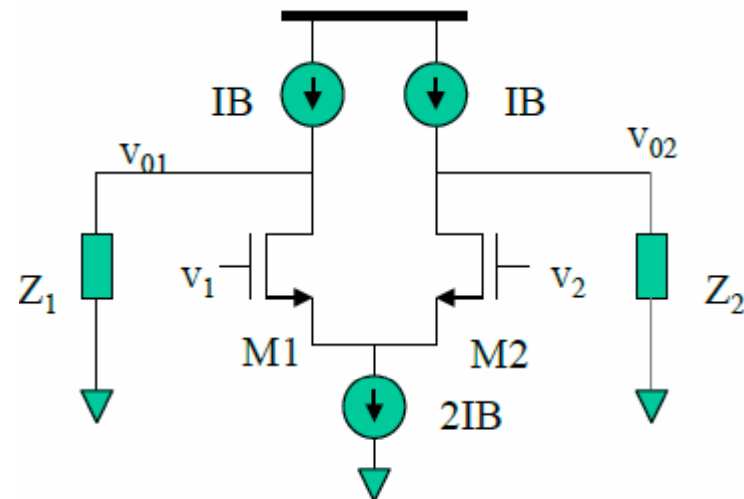
$$A_{dd} = \frac{v_{o1} - v_{o2}}{v_{i2} - v_{i1}} \bigg|_{v_{ic}=0} = \frac{g_{m1}g_{m2}}{g_{m1} + g_{m2} + Y_s} \left[Z_1 + Z_2 + \frac{Y_s}{2} \left(\frac{Z_1}{g_{m2}} + \frac{Z_2}{g_{m1}} \right) \right]$$

$$A_{dc} = \left. \frac{v_{o1} - v_{o2}}{(v_{i2} + v_{i1})/2} \right|_{v_{id}=0} = \frac{g_{m1}g_{m2}}{g_{m1} + g_{m2} + Y_s} \left[Y_s \left(\frac{Z_2}{g_{m1}} - \frac{Z_1}{g_{m2}} \right) \right]$$

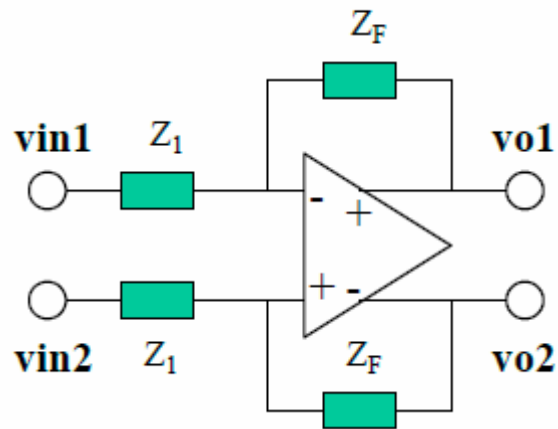
$$A_{cd} = \left. \frac{(v_{o2} + v_{o1})/2}{v_{i2} - v_{i1}} \right|_{v_{ie}=0} = \frac{g_{m1}g_{m2}}{g_{m1} + g_{m2} + Y_s} \left(\frac{1}{2} \right) \left[Z_1 - Z_2 + \frac{Y_s}{2} \left(\frac{Z_1}{g_{m2}} - \frac{Z_2}{g_{m1}} \right) \right]$$

$$A_{cc} = \left. \frac{(v_{o2} + v_{o1})/2}{(v_{i2} + v_{i1})/2} \right|_{v_{id}=0} = - \frac{g_{m1}g_{m2}}{g_{m1} + g_{m2} + Y_s} \left(\frac{1}{2} \right) \left[Y_s \left(\frac{Z_2}{g_{m1}} + \frac{Z_1}{g_{m2}} \right) \right]$$

$$CMRR = \frac{A_{dd}}{A_{dc}} \cong \frac{g_{m1} \left(1 + \frac{Z_1}{Z_2} \right)}{Y_s \left(1 - \frac{g_{m1}Z_1}{g_{m2}Z_2} \right)}$$



Fully-Differential Circuits



•Ideal voltage gain

$$A_{dd} = \frac{v_{o1} - v_{o2}}{v_{in2} - v_{in1}} = \frac{Z_f}{Z_1}$$

•Ideally even-order distortions are cancelled

•Ideally common-mode signals are rejected

•Two-Stage, Miller, Differential-In, Differential-Out Op Amp

$$OCMR = V_{DD} + |V_{SS}| - V_{DSsatN} - V_{DSsatP}$$

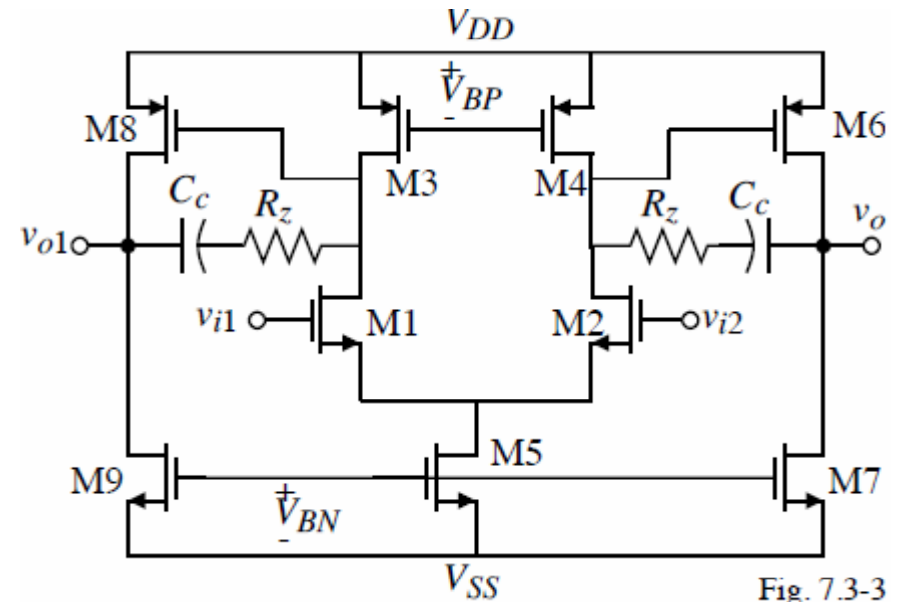
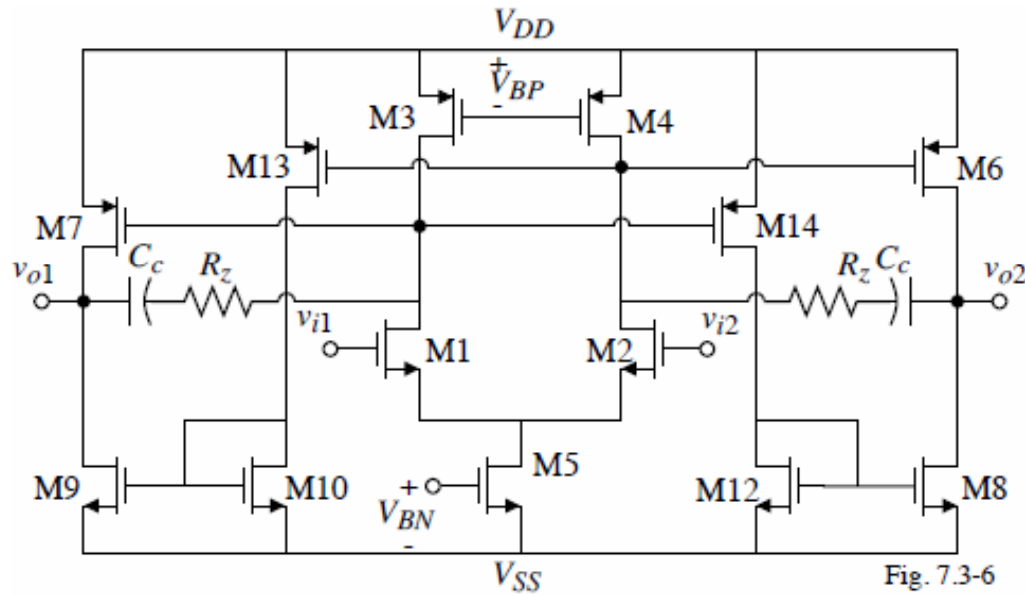


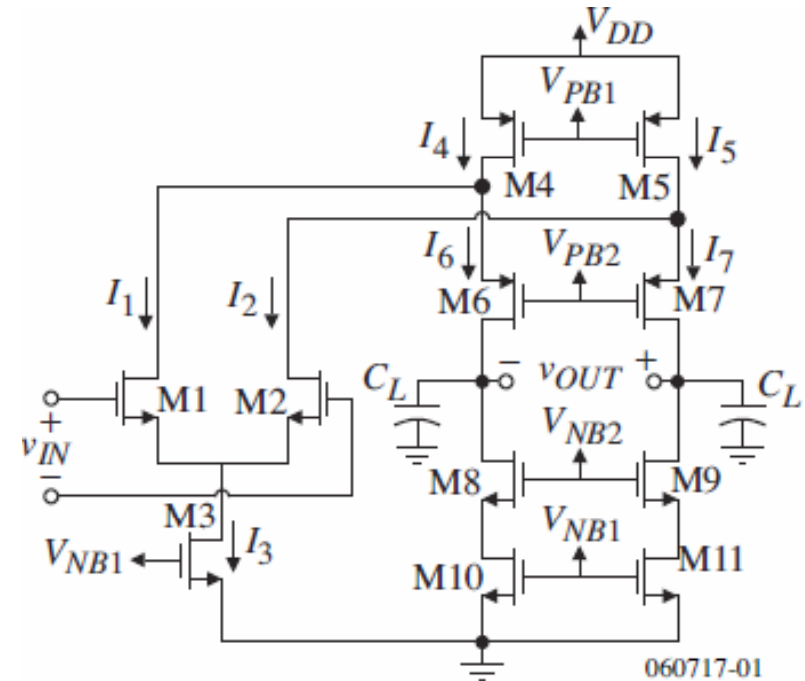
Fig. 7.3-3

- Two-Stage, Miller, Differential-In, Differential-Out Op Amp with Push-Pull Output



$$OCMR = V_{DD} + |V_{SS}| - V_{DSsatN} - V_{DSsatP}$$

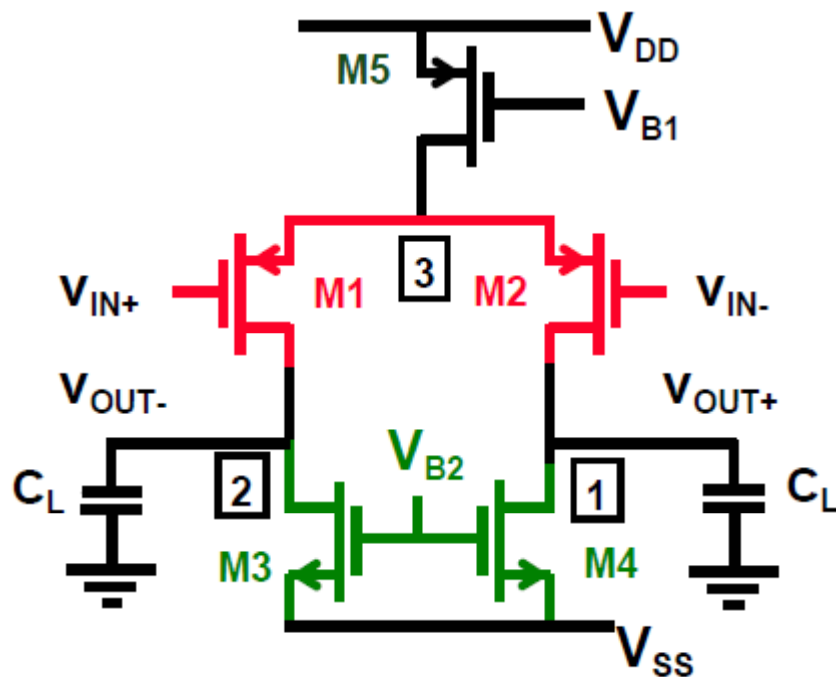
- Folded-Cascode, Differential Output Op Amp



$$OCMR = V_{DD} + |V_{SS}| - 2V_{DSsatN} - 2V_{DSsatP}$$

- Fully differential circuits are widely used due to their large available signal swing, and superior supply and substrate interference immunity.
- They need them to be able to reject the common mode disturbances generated by the digital circuits, the class-AB drivers, the clock drivers, etc.
- As a consequence, all mixed-signal circuitry requires the amplifiers to be fully-differential. However, this will cost a lot of additional power consumption. Consequently, an extra amplifier will be required to stabilize the average or common-mode output level. It is called the common-mode feedback (CMFB) amplifier. It obviously takes additional current.

▪ Simple CMOS fully-differential OTA

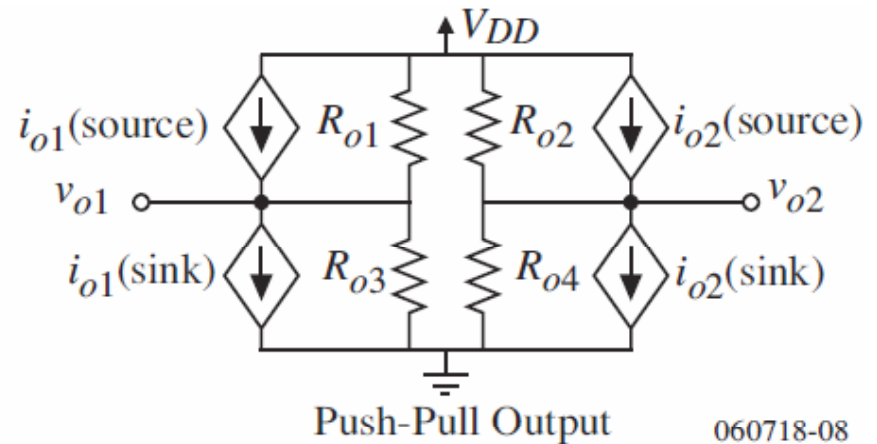
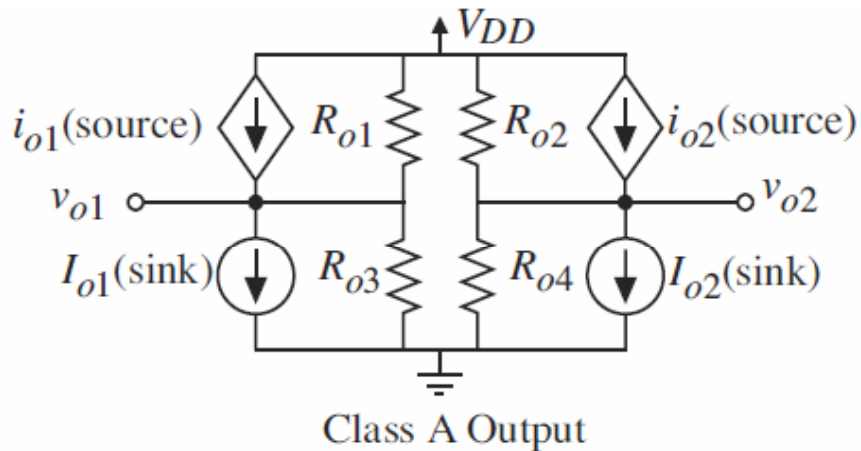


- Problem: keep M1-4 in saturation
- The biasing voltages V_{B1} and V_{B2} have to be such that all transistors are in the saturation region.
- The problem of the two biasing voltages is that they have to be matched to such a degree that the average output voltages are somewhere halfway between the supply voltages, to keep all transistors in saturation, even for a large output swing
- Control V_{OUTCOM} Control I_{DS5}

❖ Common mode output voltage stabilization

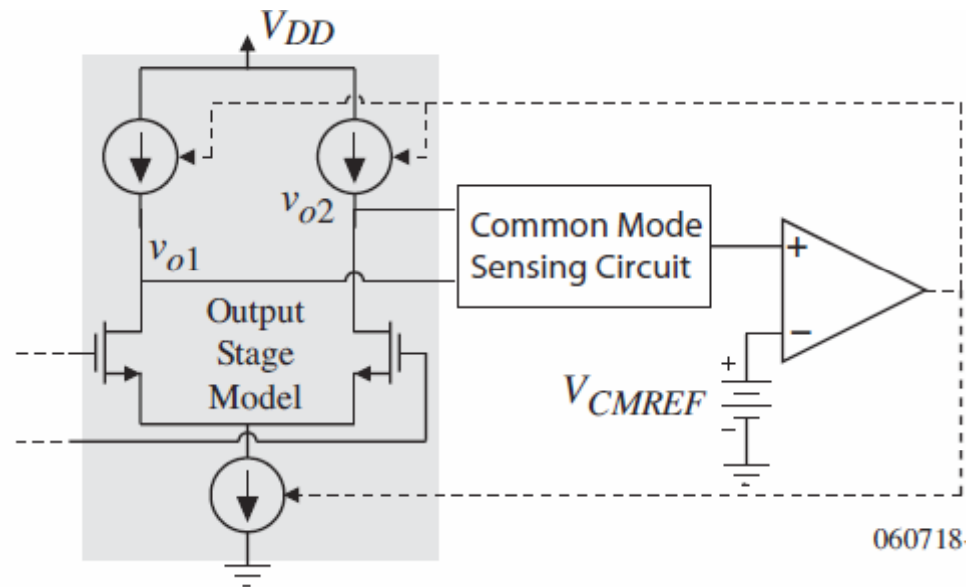
➤ Common Mode Feedback Circuits

- The common mode output voltage is stabilized by sensing the common mode output voltage and using negative feedback to adjust the common mode voltage to the desired value.
- Model for the Output of Differential Output Op Amps



- Roi represents the self-resistance of the output sink/sources.
- If the common mode output voltage increases the sourcing current is too large.
- If the common mode output voltage decreases the sinking current is too large.

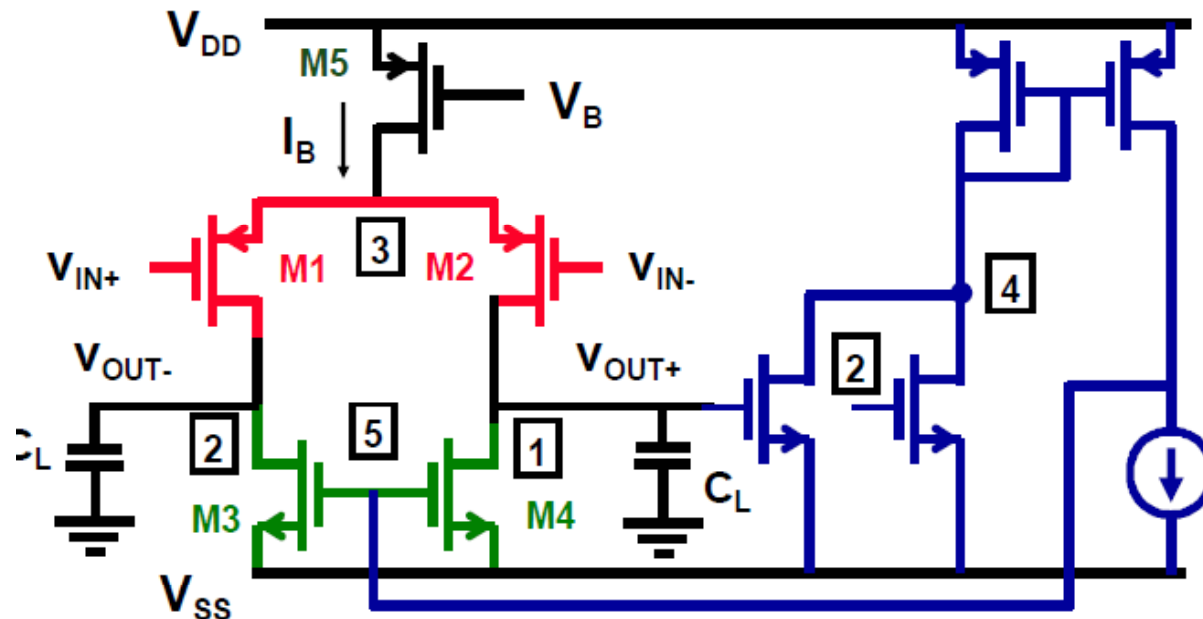
- Conceptual View of Common-Mode Feedback



- Function of the common-mode feedback circuit:

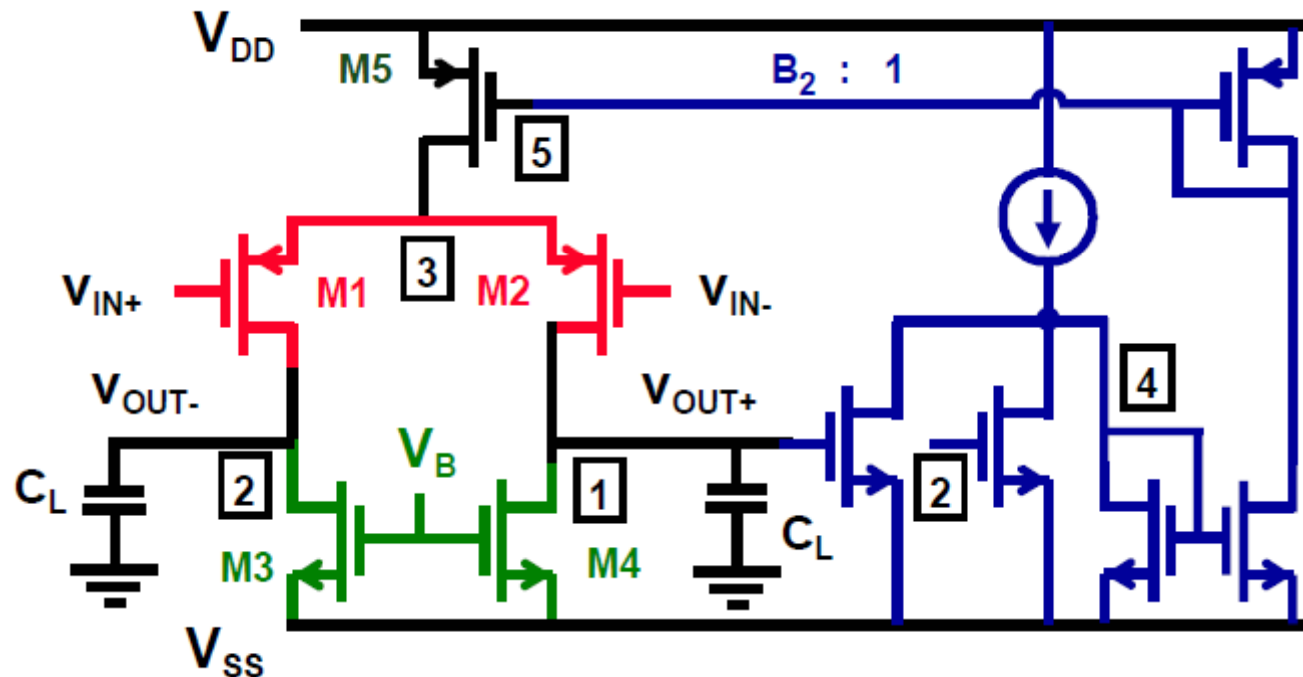
- 1) If the common-mode output voltage increases, decrease the upper currents sources or increase the lower current sink until the common-mode voltage is equal to V_{CMREF}
- 2) If the common-mode output voltage decreases, increase the upper currents sources or decrease the lower current sink until the common-mode voltage is equal to V_{CMREF}

▪ Simple CMOS fully-differential OTA with CMFB-1



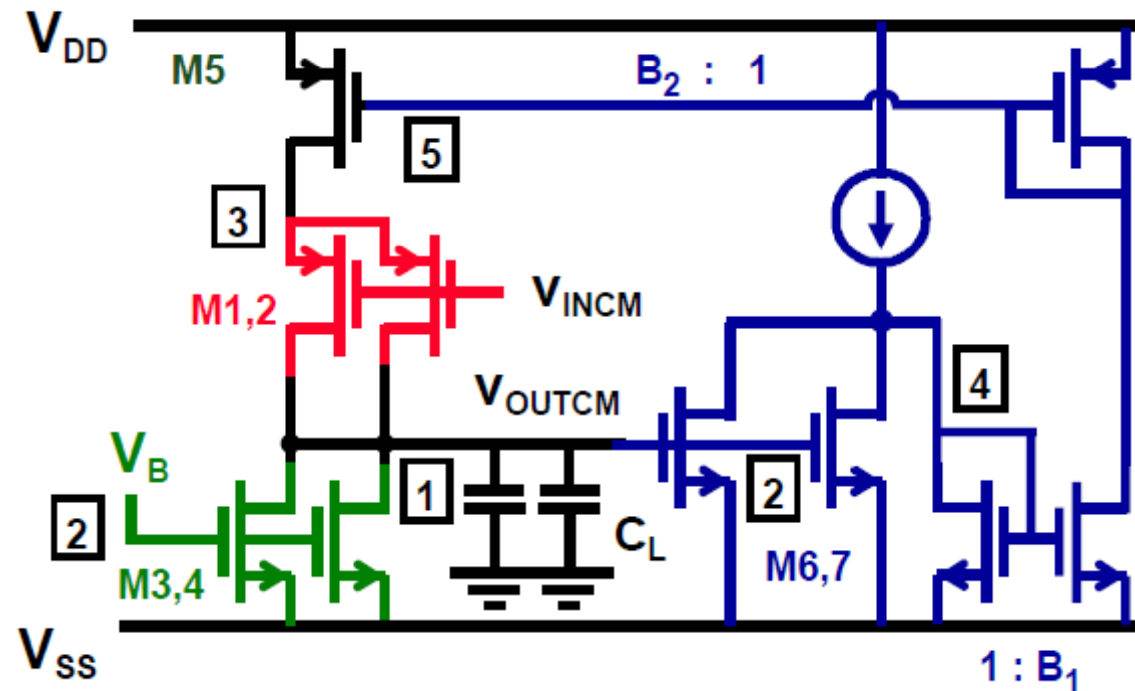
- Both output voltages are measured. Since we only want feedback on the common-mode signals, we have to cancel out the differential signals. This is done at node 4.
- Now we have to close the loop with an amplifier, and feed it to a common-mode point. Any biasing point in the circuit can be used for that. For this amplifier it is node 5.
- Clearly, part of the circuit belongs to both the common-mode and the differential amplifier. For example, transistors M3 and M4 are DC current sources for the differential signals, but single-transistor amplifiers for the common-mode signals.
- Also, the CMFB amplifier is always connected in unity-gain feedback. Nodes 1 and 2 are at the same time the input and output of the CMFB amplifier. It may thus require more power to ensure stability.
- The differential amplifier is evidently shown without feedback

▪ Simple CMOS fully-differential OTA with CMFB-2



- Again, the output voltages are measured. The differential signals are cancelled out and the CMFB loop is closed by means of an amplifier.
- Now transistors M1 and M2 are common to both amplifiers. They function as a (differential) amplifier for differential signals, but as cascodes for the common-mode signals.
- The common-mode equivalent circuit is easily found by putting all differential devices in parallel and connecting them to the common-mode input signals

▪ Common-mode feedback equivalent circuit



- Actually, the open-loop gain is $B_1 B_2 g_{m5} R_{n1}$. This gain is not so high but only a small amount of gain is needed.
- The stabilization of the common-mode output voltage does not need to be so accurate.
- The outputs will both be at $V_{GS5,6}$ above the negative supply.
- The GBW_{CM} will evidently be given by the $B_1 B_2 g_{m5} / (2\pi C_L)$. We have two input transistors M5 and M6 but also two load capacitors. The GBW_{CM} can therefore be made quite high, at the cost of a lot of power consumption though!
- Finally, it is important to note that the gain of the CMFB amplifier is used to increase the common-mode rejection ratio.

▪ Requirements fully-differential amplifiers

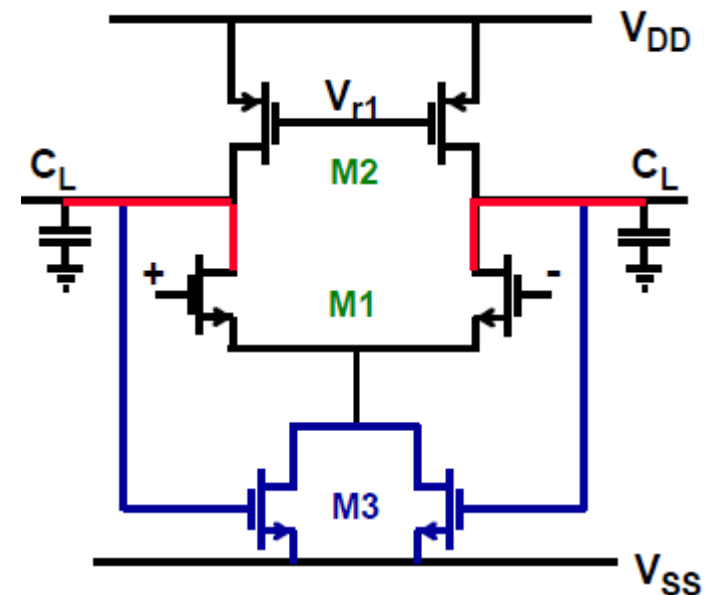
- High speed : $GBW_{CM} > GBW_{DM}$

Indeed, if the common mode amplifier were slow, only providing DC biasing, then a high-speed spike on the supply line or the substrate would throw the input devices or the active loads in the linear region. Slow common-mode feedback would then take too much time to restore the biasing in the input stage. During all this time, the high-speed differential amplifier would be out of operation. This why this specification comes first.

- Output swing limited by : Output swing of differential-mode amp, input range of common-mode amp and low power $P_{CM} < P_{DM}$.
- Requiring the GBW_{CM} to be as large as the GBW_{DM} will require a lot of power, directly conflicting with the last specification. We will see that there is no easy way of avoiding this compromise. In principle, a fully-differential amplifier simply doubles the power consumption.

■CMFB amplifier with linear MOSFET-1

- This is probably the simplest possible CMFB amplifier.
- It consists of a differential pair, the current source of which consists of two transistors M3 in the linear region, with a $V_{DS3} < V_{GS3} - V_T$.
- The three functions of the CMFB amplifier are clearly distinguished.
- The output voltages are measured by the two transistors M3. Their Drains are connected to cancel the differential signal and the feedback loop is closed.



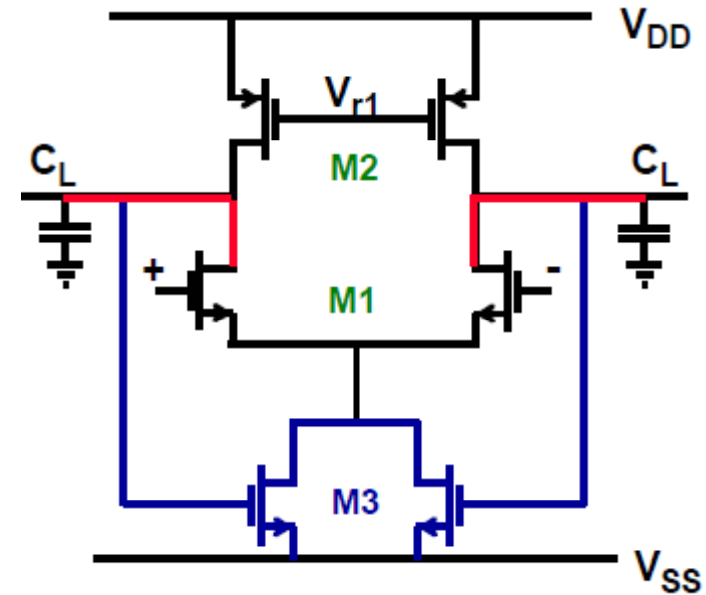
- The input transistors M1 of the differential pair function as cascodes for the CMFB.

$$V_{DS} \approx 200 \text{ mV}, I_{DS} = \beta V_{DS} (V_{GS} - V_T)$$

$$g_{m3} = \beta V_{DS}$$

$$GBW_{DM} = \frac{g_{m1}}{2\pi C_L}$$

$$GBW_{CM} = \frac{g_{m3}}{2\pi C_L}$$



- It is clear that in the linear region, the transconductances are much smaller than in the saturation region. The common-mode GBW_{CM} is therefore smaller than the GBW_{DM} . This is a disadvantage!
- Why do the transistors M3 operate in the linear region?
- There are two reasons:
 - ✓ First of all, to have an output voltage in the middle, we need a large V_{GS3} . So as not to loose a large voltage drop, we need a small V_{DS3} . Clearly M3 must be in the linear region.
 - ✓ The other reason is linearity. We need a linear cancellation of the differential signal to avoid the reduction of the differential gain because of the feedback. Transistors in the linear region are very linear indeed!

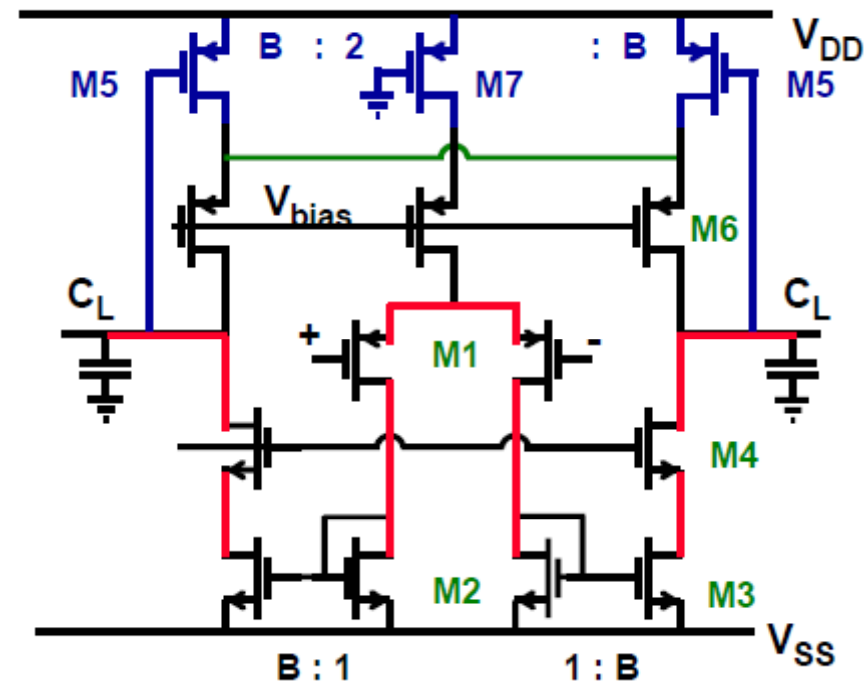
- The differential amplifier is a symmetrical amplifier, whereas the CMFB amplifier is the same as before. It uses transistors M5 in the linear region.
- By matching the transistors M5 to M7, the output voltages will be around zero. Assume then, that we have a B factor of three. Transistor M5 is then 50% larger than transistor M7. Its current is also 50% larger than in transistor M7. Their VDS voltages are the same because of cascodes M6. Their VGS values must also be the same. Since the Gate of M7 is connected to ground, the output voltages must also be around ground.
- Moreover, the output voltages are better defined (by matching) than in the previous circuit, where they depend on transistor sizes.

$$V_{SD5} \approx 200 \text{ mV}, I_{DS5} = \beta V_{SD5} (V_{SG5} - |V_{TP}|)$$

$$g_{m5} = \beta V_{SD5}$$

$$GBW_{DM} = B \frac{g_{m1}}{2\pi C_L}$$

$$GBW_{CM} = \frac{g_{m5}}{2\pi C_L} < GBW_{DM}$$



- Two-Stage, Miller, Differential-In, Differential-Out Op Amp with Common-Mode Feedback

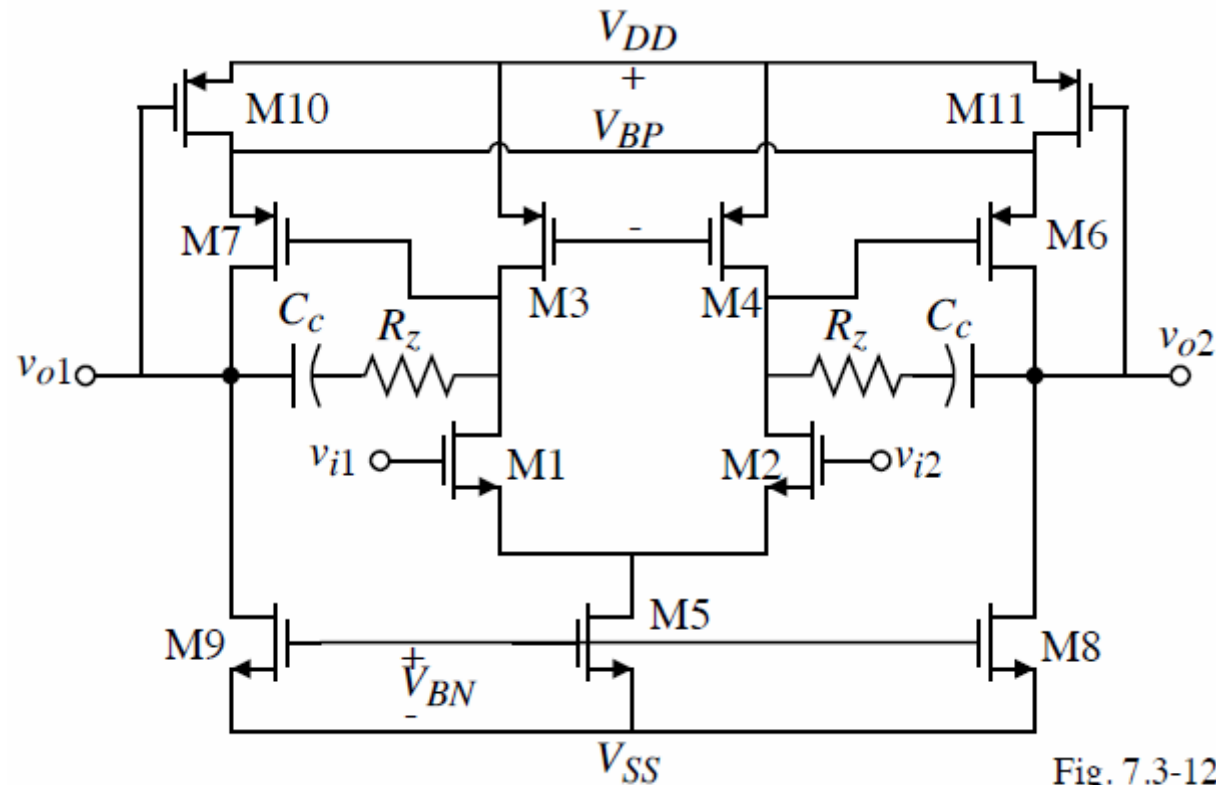


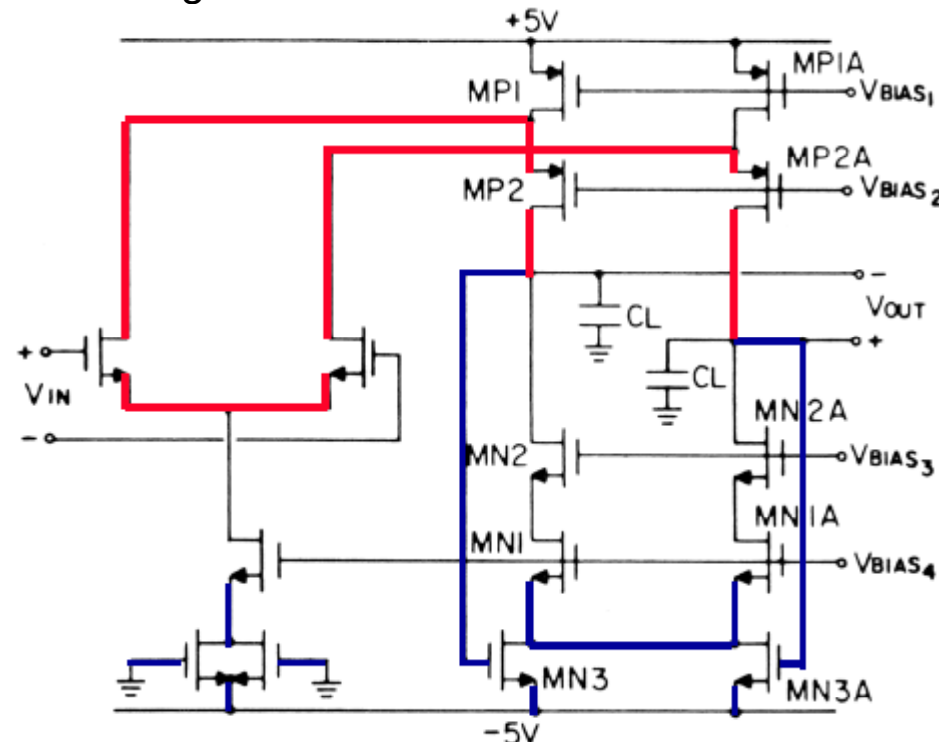
Fig. 7.3-12

- The loop gain of the common-mode feedback loop is

$$LG_{CM} \approx -\frac{g_{m10}}{g_{ds9}}$$

- If the CM voltage should decrease, the source-gate voltages of M10 and M11 are decreased.
- This causes more current to be injected into the top connection of the sourcing current sources, R_{o7} and R_{o6} .
- Assuming balanced conditions, this current splits and flows through R_{o7} and R_{o9} and through R_{o6} and R_{o8} .

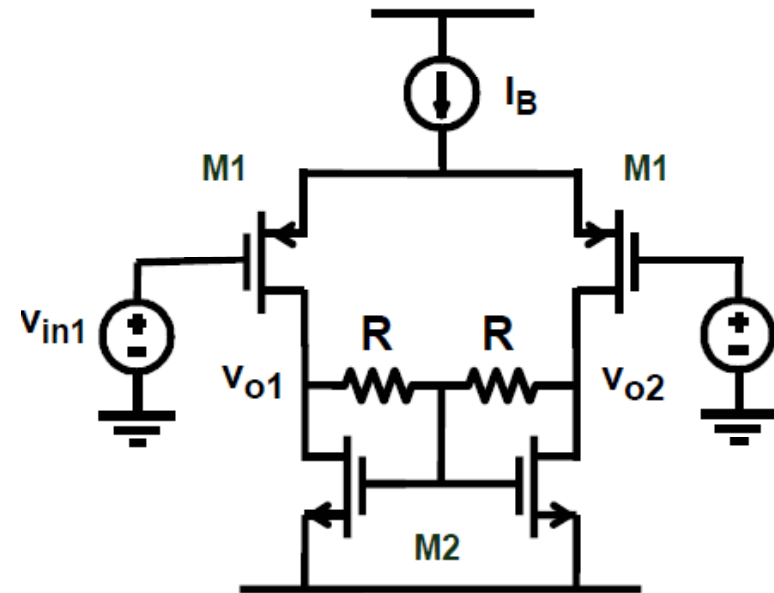
- The same CMFB amplifier can be applied to a fully differential folded cascode stage as well.
- Transistors MN3 operate in the linear region.
- The output voltages will be around 0 because the transistors MN3 are matched to the two transistors in the current source at the input. Their Gates are connected to ground. The currents in all branches are the same. The VGS values are also the same. The output voltages are therefore around ground.



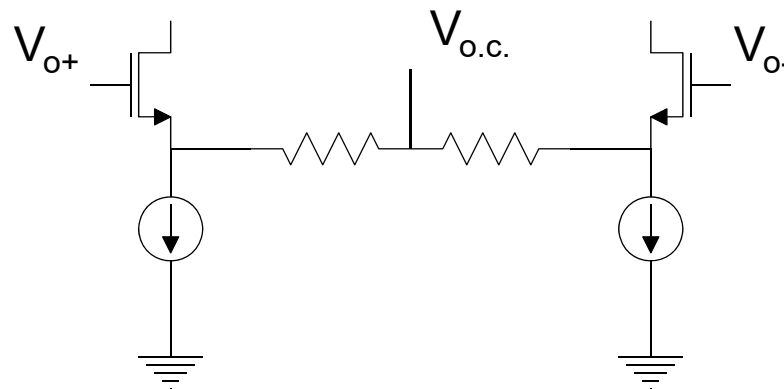
✓ The main advantage of this first principle of CMFB is that no additional power is required. The main disadvantage is that this CMFB amplifier may not be sufficiently fast, depending on the application.

➤ Fully-differential amplifier with resistive CMFB

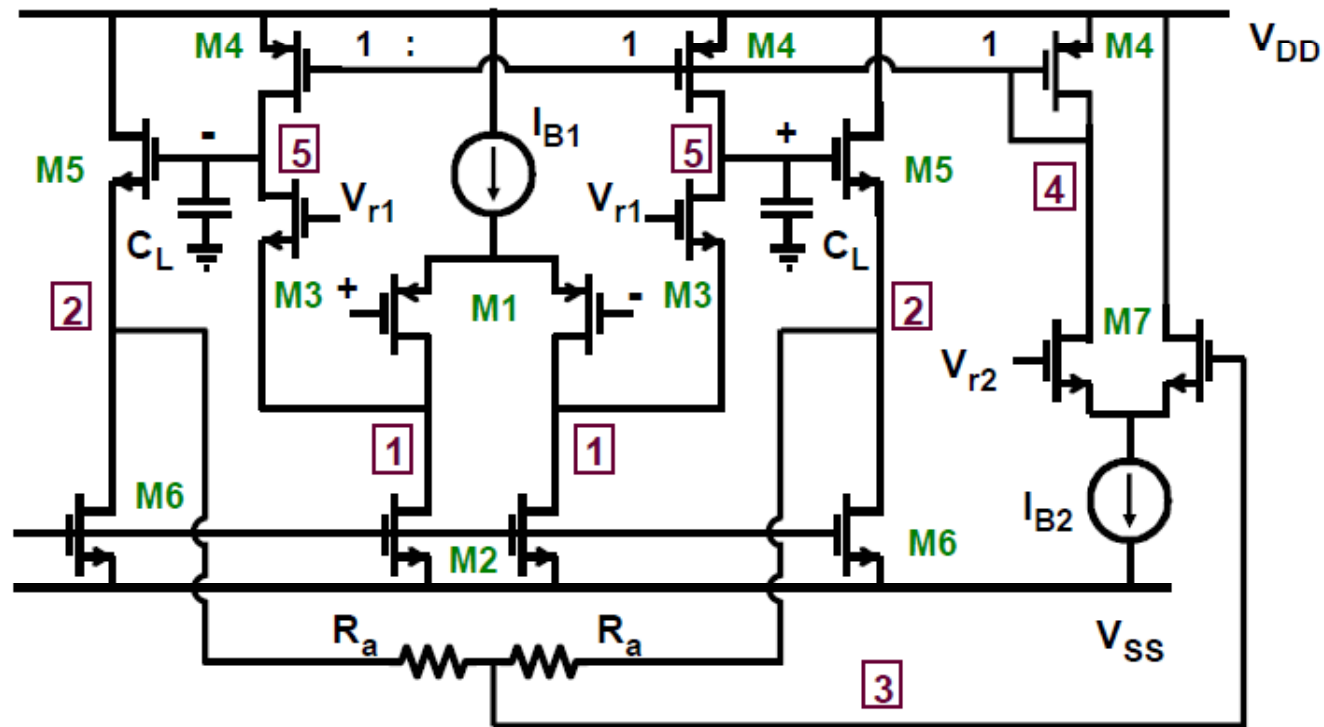
- This fully-differential amplifier uses two equal resistors R to cancel out the differential signals. In this way a common-mode biasing voltage is obtained for the gates of transistors $M2$.
- The main disadvantage is that the resistors R must be increased in size to ensure a lot of gain.
- An easy solution is to insert source followers between the drains of the input transistors $M1$ and the two resistors R . Smaller values of R are then possible.



Simple implementation: source follower



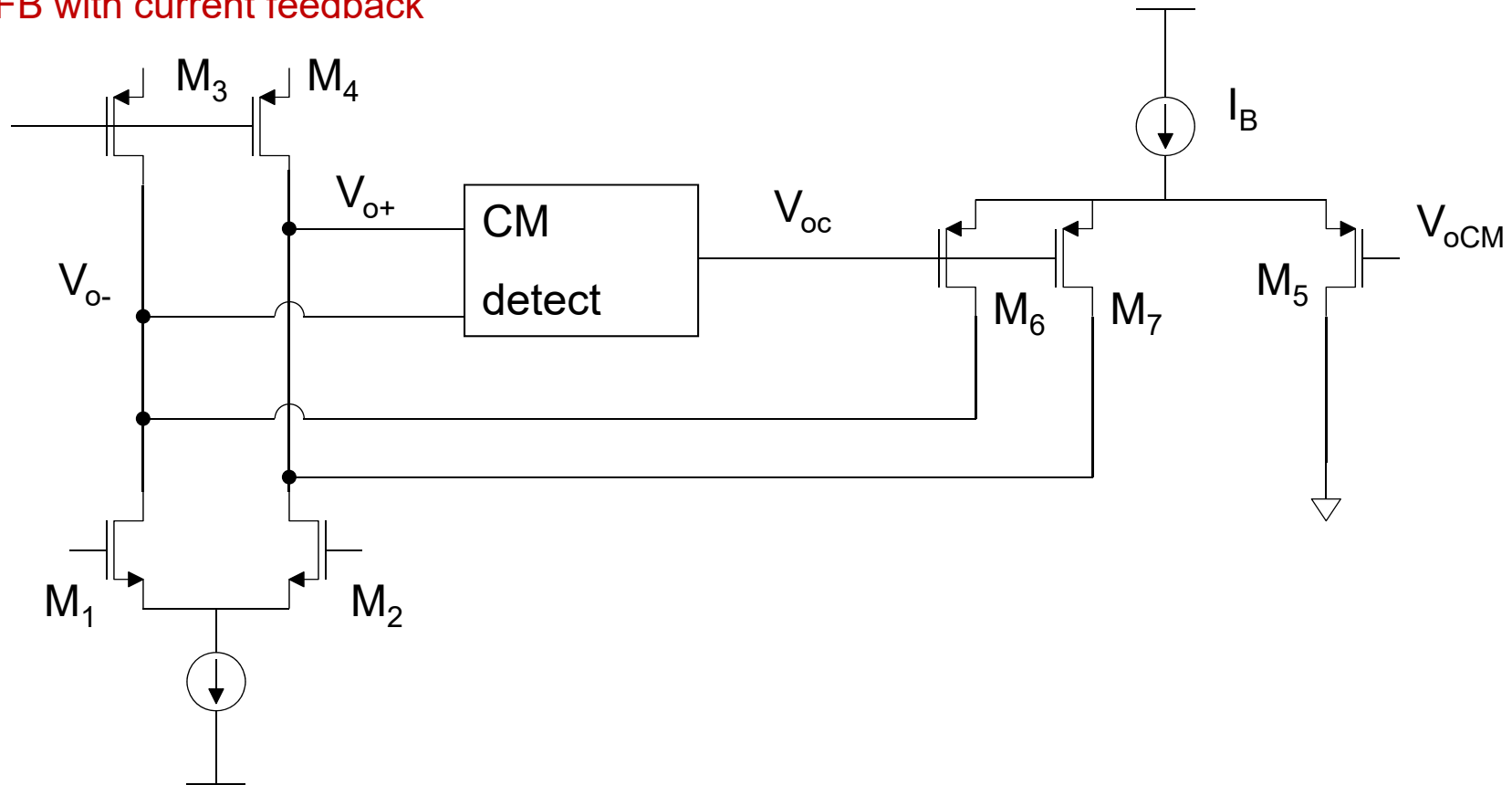
Fully-differential folded cascode with source follower



$L_{\min} = 0.8 \mu\text{m}$; $V_T = 0.7 \text{ V}$
 $K'_n = 60 \mu\text{A/V}^2$ & $K'_p = 30 \mu\text{A/V}^2$
 $V_{En} = 4 \text{ V}/\mu\text{m}$ & $V_{Ep} = 6 \text{ V}/\mu\text{m}$

$\text{GBW}_{\text{DM}} = 10 \text{ MHz}$ $C_L = 3 \text{ pF}$
 $\text{GBW}_{\text{CM}} = 20 \text{ MHz}$
 all PM $> 70^\circ$
 $V_{\text{DD}}/V_{\text{SS}} = \pm 1.5 \text{ V}$

➤ CMFB with current feedback

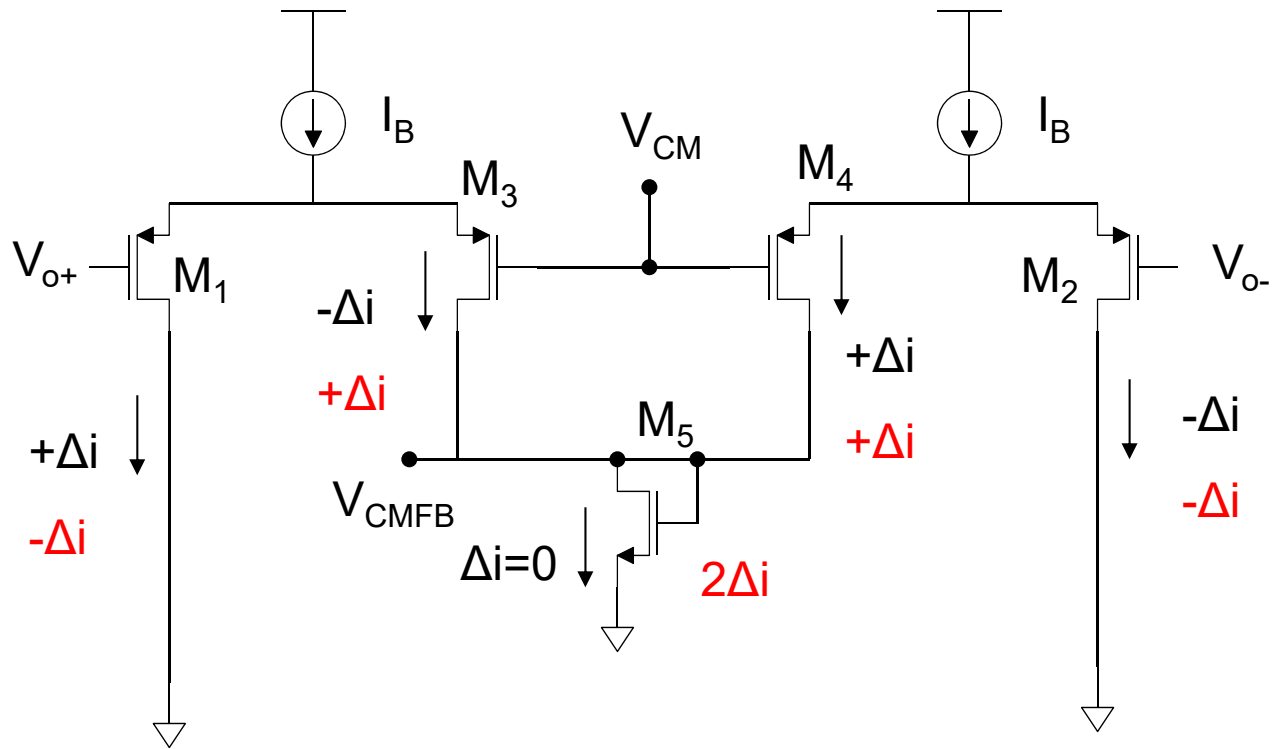


•M6, M7 matched
$$I_{c6,7} = \frac{I_B}{4} - \frac{g_{m6}}{2}(V_{oc} - V_{0cm})$$

•The CMFB loop will adjust $I_{c6,7}$ so that $|I_{D3}| + |I_{D4}| + 2I_{c6,7} = I_{D5}$

$$V_{oc} = V_{0cm} \Rightarrow 2I_{c6,7} = I_B / 2 \Rightarrow |I_{D3}| + |I_{D4}| + I_B / 2 = I_{D5}$$

➤ CMFB using two differential pairs

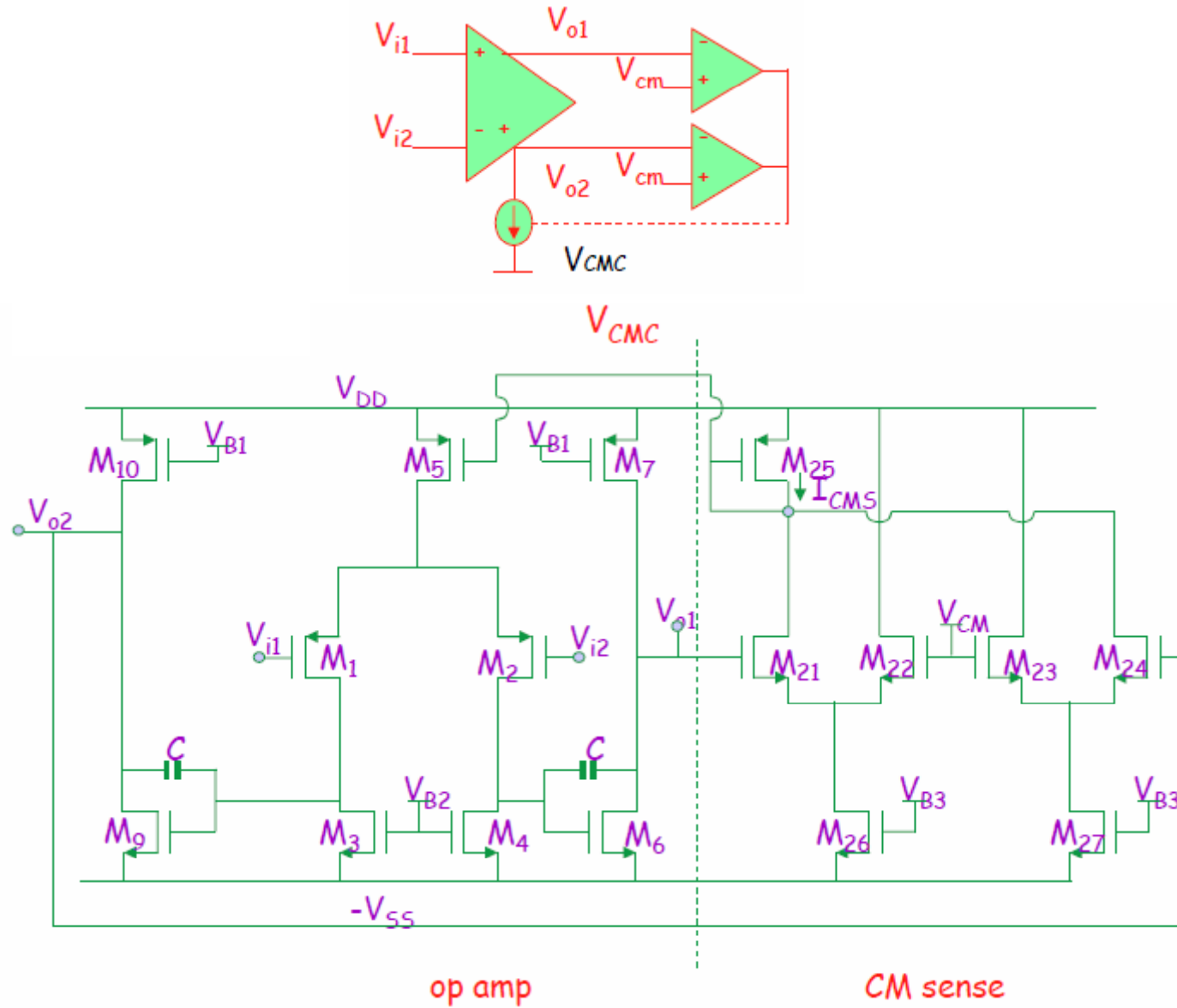


- Differential V_o : V_{o+} ↓ by ΔV_o , V_{o-} ↑ by Δv_o
- Common mode V_o : V_{o+} ↑ by ΔV_o , V_{o-} ↑ by Δv_o

$$g_{m1} = g_{m2} = g_{m3} = g_{m4} \Rightarrow \Delta i = g_{m1} \frac{\Delta V_o}{2}$$

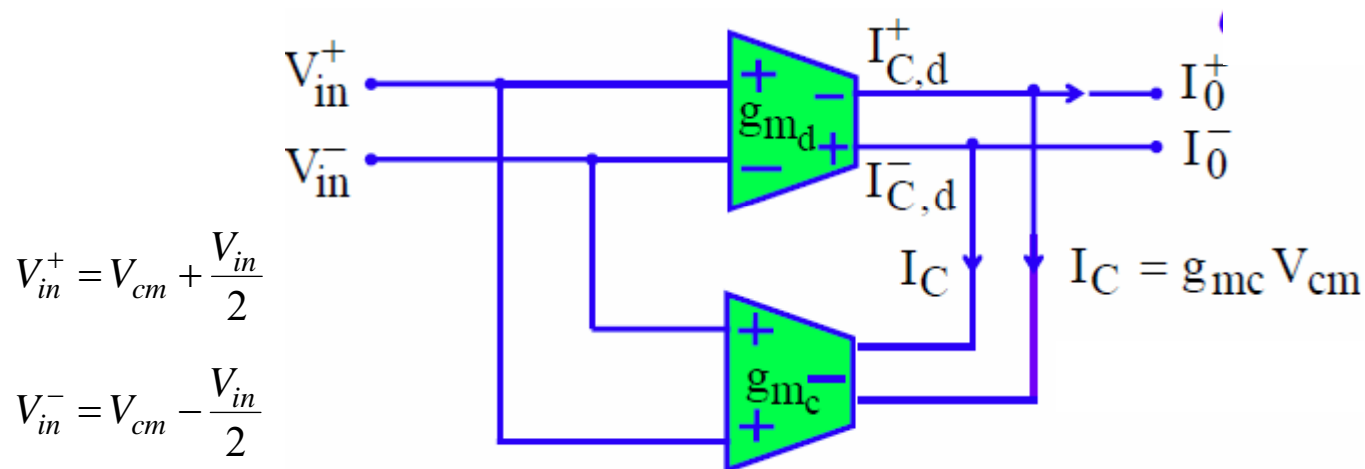
$$\Delta V_{CMFB} = \frac{1}{g_{m5}} \cdot 2\Delta i = \frac{g_{m1}}{g_{m5}} \cdot \Delta V_o$$

- Example of a compensated Op Amp and a CM sense circuit with two differential pairs



➤ What is a common-mode feed-forward correction circuit ?

• A common mode feed-forward circuit is a circuit sensing the input voltage. Then this input common-mode current is added at each of the two output terminals (or applied to an internal node of the amplifier) with the purpose to cancel the output common-mode current component.

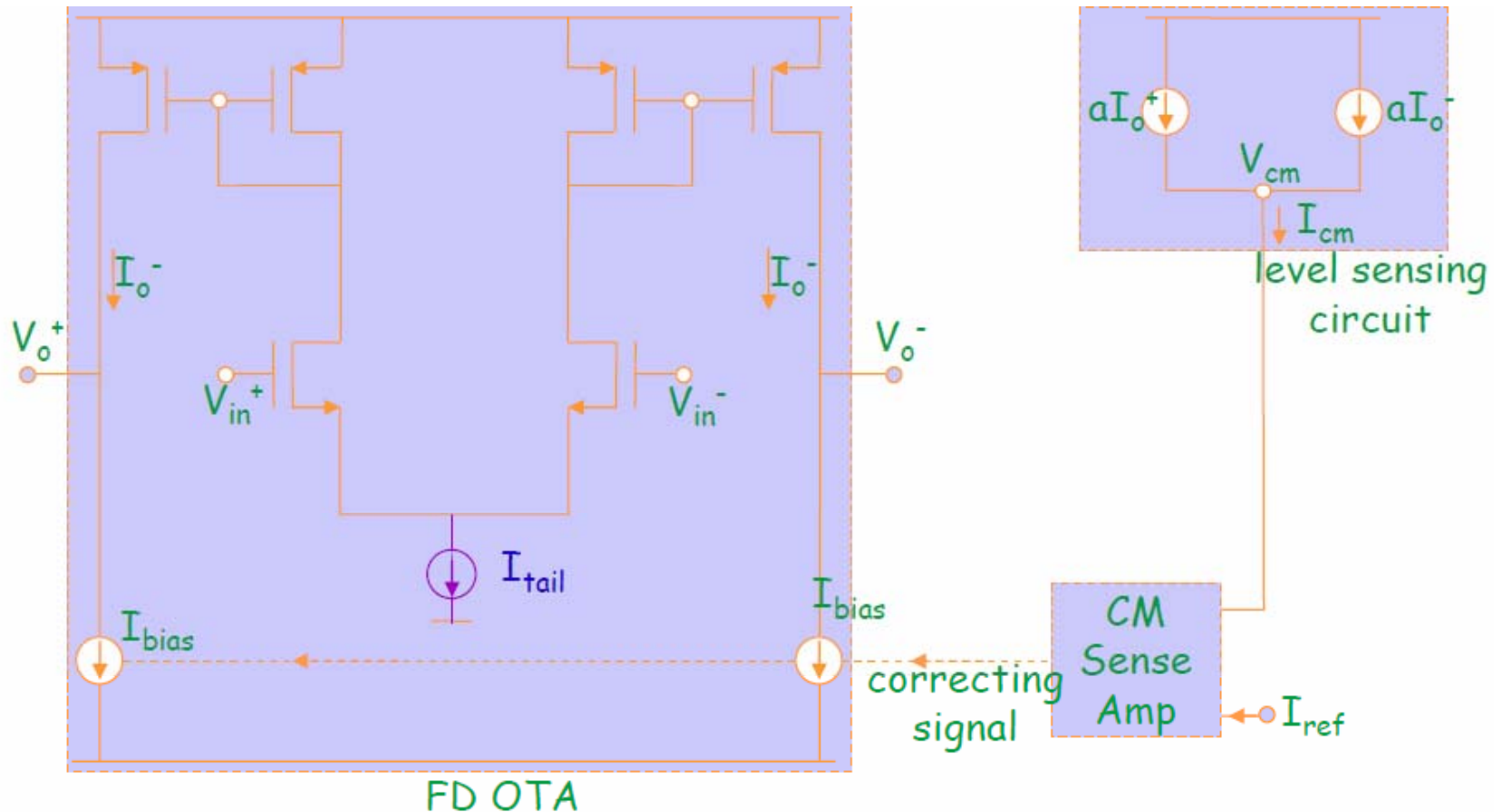


$$I_{C,d}^+ = g_{md} \left(V_{cm} + \frac{V_{in}}{2} \right) \quad I_{C,d}^- = g_{md} \left(V_{cm} - \frac{V_{in}}{2} \right)$$

$$I_0^+ = I_{C,d}^+ - I_C = g_{md} \left(V_{cm} + \frac{V_{in}}{2} \right) - I_C \quad I_0^- = I_{C,d}^- - I_C = g_{md} \left(V_{cm} - \frac{V_{in}}{2} \right) - I_C$$

$$g_{mc} = g_{md} \Rightarrow I_0^+ = g_{md} \frac{V_{in}}{2}, I_0^- = -g_{md} \frac{V_{in}}{2}$$

- Let us explore how a common-mode feedforward can be sensed and then applied. Consider a fully differential OTA with two current-mirrors

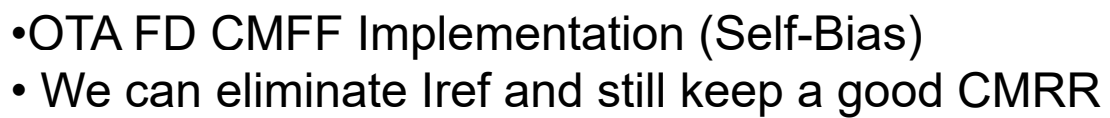


- Correcting signal can be voltage or current. Note that I_{o+} , and I_{o-} are equal to

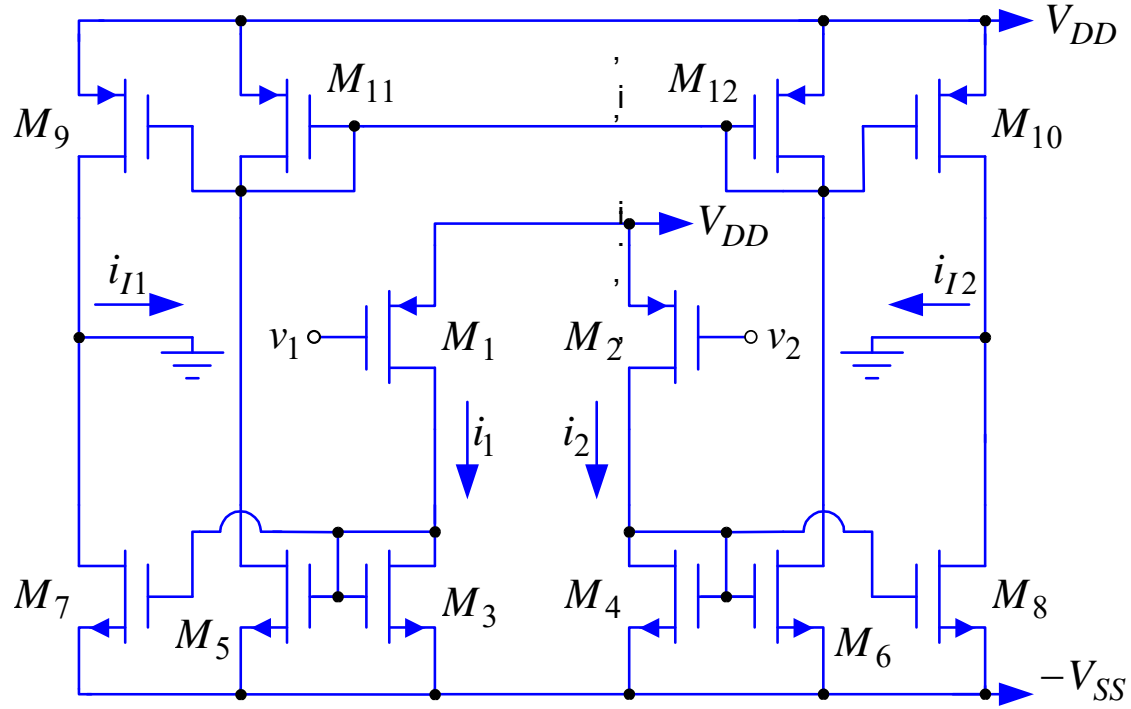
$$I_{o+} = g_m (V_{in+} - V_{in-}) \quad I_{o-} = g_m (V_{in-} - V_{in+})$$

- That is, we are sensing the input voltage. We are not sensing the output voltage. In practice the value of a is $a = 1$ or $a = 1/2$.

- Current addition transformed into a V_{cm}
- Since $V_{reference} = 0$, $V_{correction} = V_{cm}$ and can be applied to MY' and MY



$$i_I = f(i_1, i_2) = ?$$



$$i_7 = i_5 = i_3 = i_1 \quad i_8 = i_6 = i_4 = i_2 \quad i_{11} = i_{12} = \frac{1}{2}(i_1 + i_2)$$

$$i_9 = i_{11} \quad i_{10} = i_{12}$$

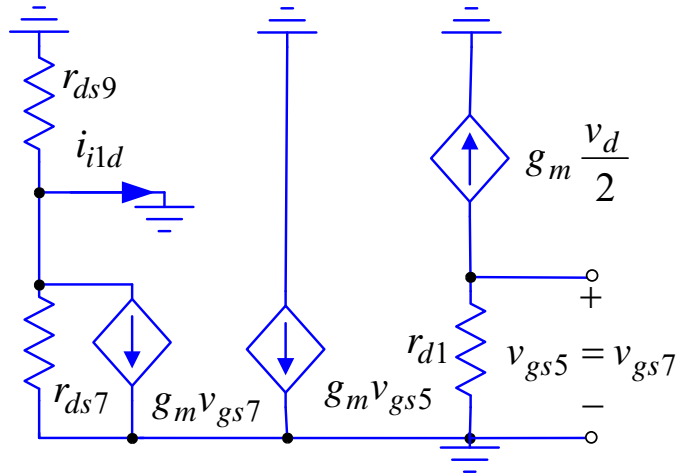
$$i_{I1} = i_{10} - i_8 = \frac{i_1 + i_2}{2} - i_2 = \frac{i_1 - i_2}{2} \quad i_{I2} = i_9 - i_7 = \frac{i_1 + i_2}{2} - i_1 = \frac{i_2 - i_1}{2}$$

$$i_1 = \frac{B}{2}(v_{GS1} - V_{TP})^2 = \frac{B}{2}(v_{GS1} + V_T)^2 \quad i_2 = \frac{B}{2}(v_{GS2} - V_{TP})^2 = \frac{B}{2}(v_{GS2} + V_T)^2$$

$$i_{I1} = \frac{i_1 - i_2}{2} = \frac{B}{2}(v_2 - v_1) \left(V_{DD} - \left(\frac{v_1 + v_2}{2} + V_T \right) \right) \quad i_{I2} = \frac{i_2 - i_1}{2} = -\frac{B}{2}(v_2 - v_1) \left(V_{DD} - \left(\frac{v_1 + v_2}{2} + V_T \right) \right)$$

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$$g_d = i_i / v_d = ?$$



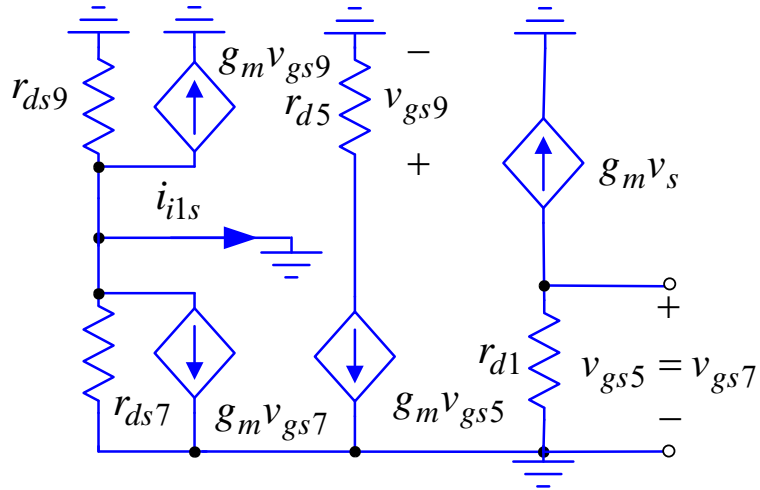
$$v_{gs5} = v_{gs7} = -r_{d1} g_m \frac{v_d}{2} \quad r_{d1} = r_{ds1} \parallel r_{ds3} \parallel \frac{1}{g_m} \approx \frac{1}{g_m}$$

$$v_{gs5} = v_{gs7} = -\frac{v_d}{2} \quad i_{i1d} = -g_m v_{gs7} = g_m \frac{v_d}{2}$$

$$g_{md1} = \frac{i_{i1d}}{v_d} = \frac{g_m}{2} \quad g_{md2} = \frac{i_{i2d}}{v_d} = -\frac{g_m}{2}$$

$$g_d = (i_{i1} - i_{i2}) / v_d = g_m$$

$$g_s = i_i / v_s = ?$$



$$v_s = \frac{v_1 + v_2}{2} \quad v_{gs9} = -r_{d5} g_m v_{gs5}$$

$$r_{d5} = r_{ds11} \parallel r_{ds5} \parallel \frac{1}{g_m} \approx \frac{1}{g_m} \quad v_{gs5} = v_{gs7} = -\frac{1}{g_m} g_m v_s = -v_s$$

$$v_{gs9} = -\frac{1}{g_m} g_m (-v_s) = v_s$$

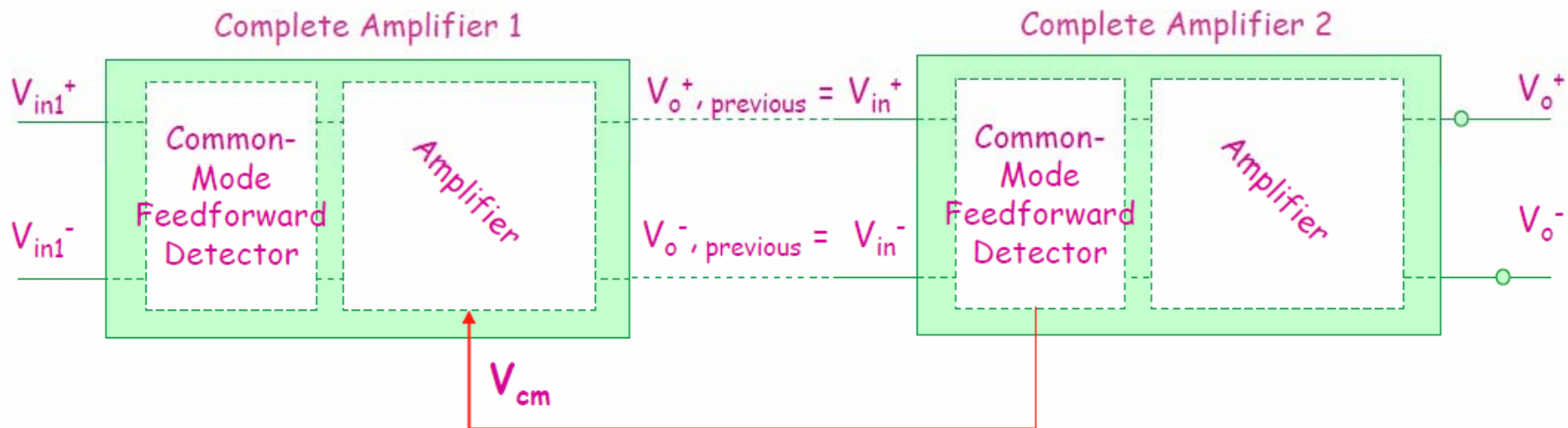
$$i_{i1s} = -g_m v_{gs7} - g_m v_{gs9} = -g_m (v_{gs7} + v_{gs9})$$

$$i_{i1s} = -g_m (-v_s + v_s) \approx 0$$

$$CMRR_{ideal} \rightarrow \infty$$

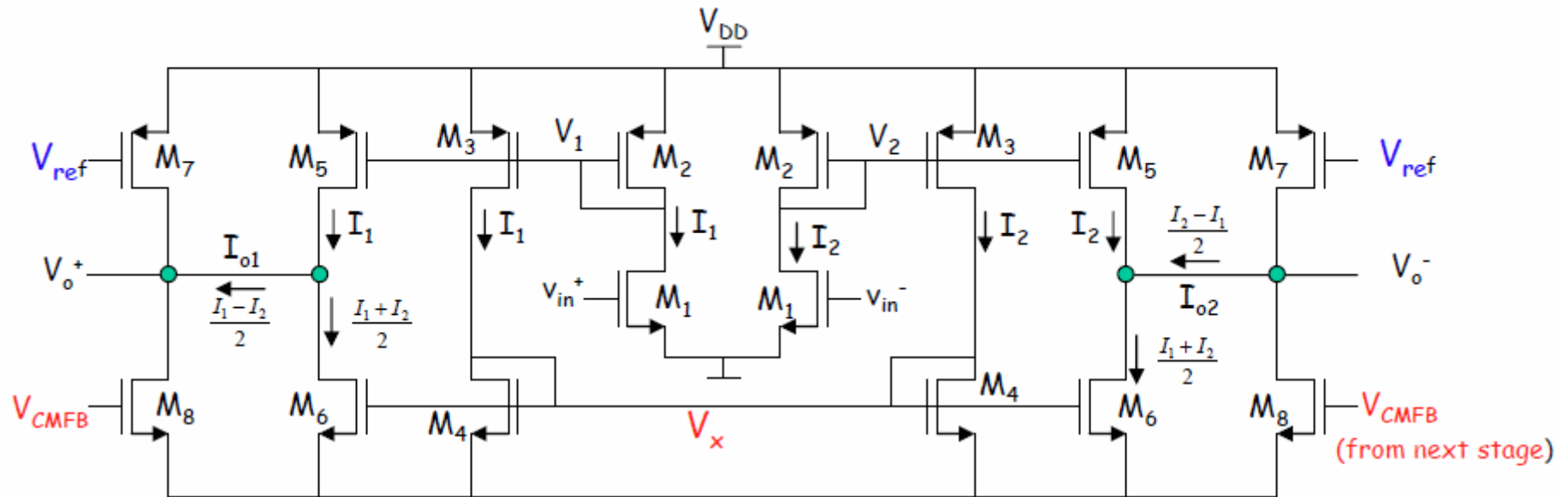
➤ Common feedback of more than one amplifier and their interconnections

- When several fully differential amplifiers are used in series, for high-order filters for example, there is no need to have CMFB around each stage separately. In order to save power, CMFB can be applied over two differential amplifiers in series, as shown in this slide.
- Observe that only one CMFB circuit is needed per output. If the Amp 1 is connected with a CMFB, any other amplifier connected to this amplifier does not need the extra CMFB.
- Furthermore, in some architectures the CM detector is a feedforward and forms part of the amplifier. An example of this type has been discussed before i.e., the Fully Balanced 4 current-mirror OTA.
- Now, the average output voltage is measured at the output of the second amplifier, and applied to the common-mode input of the first amplifier. Since the common-mode output of the first amplifier is used to set the biasing of the second one, all common-mode levels are well defined.

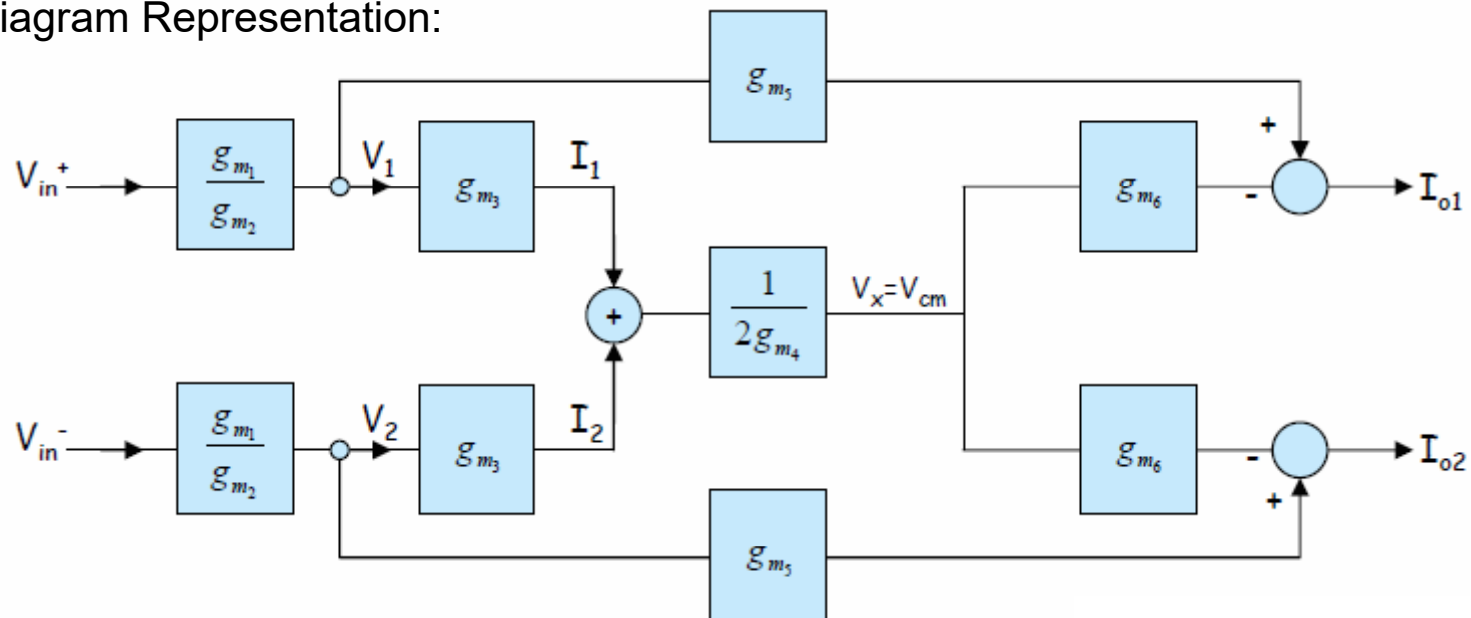


- Next OTA is detecting the common mode from this OTA and feeding back to this OTA.

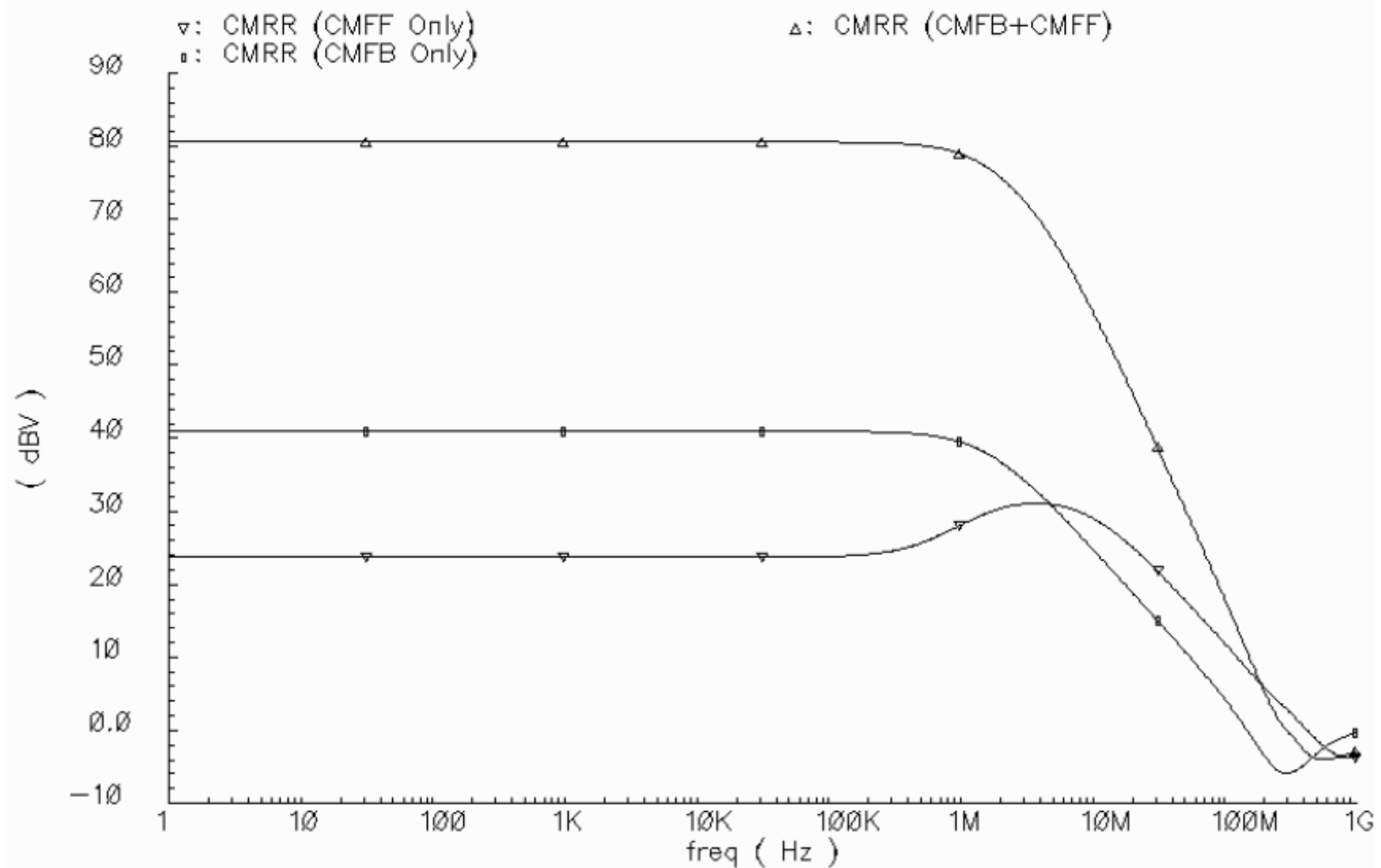
- Fully Balanced 4 current-mirror OTA



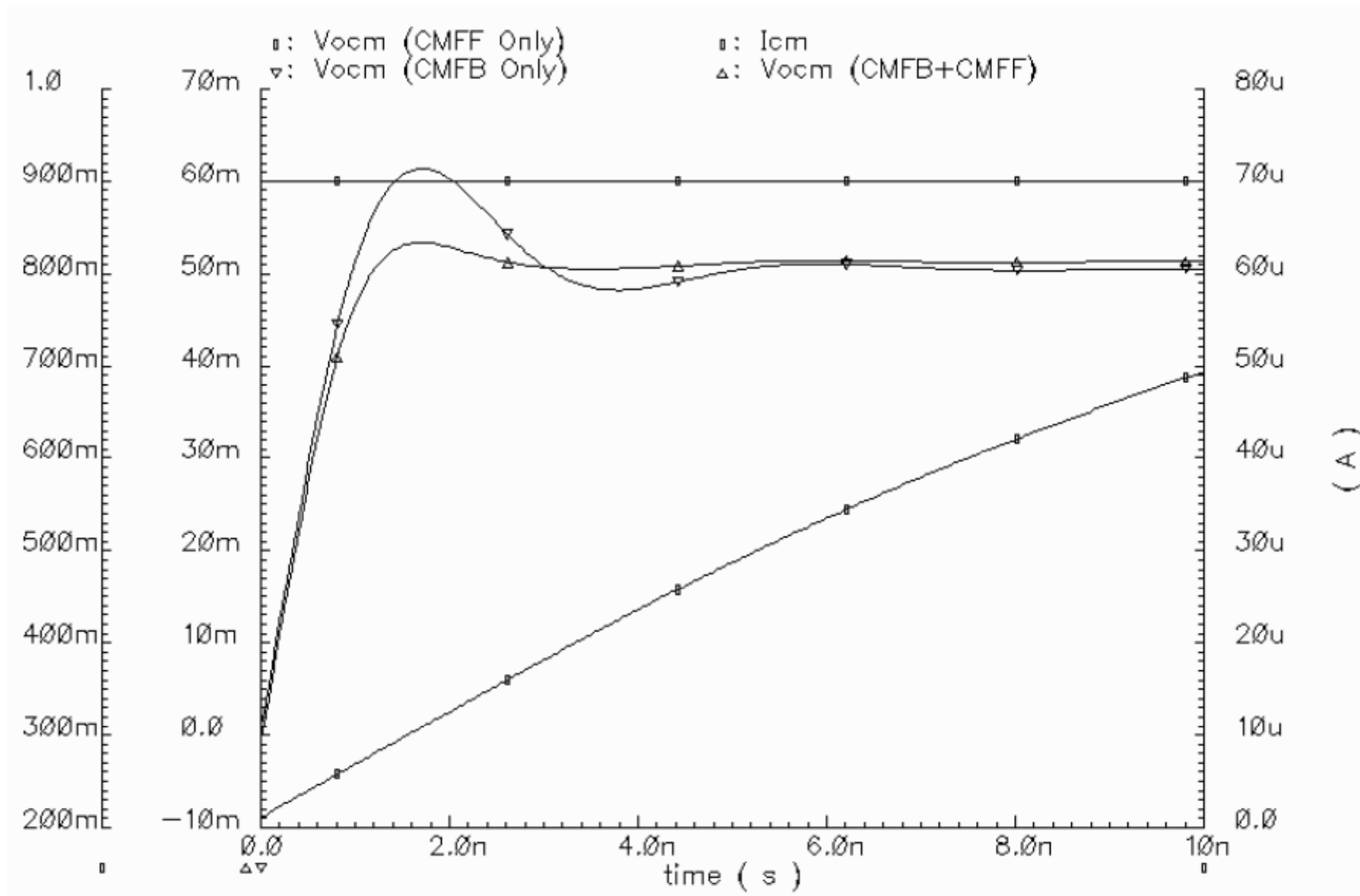
- Block Diagram Representation:



•Common-Mode Rejection Ratio (CMRR):

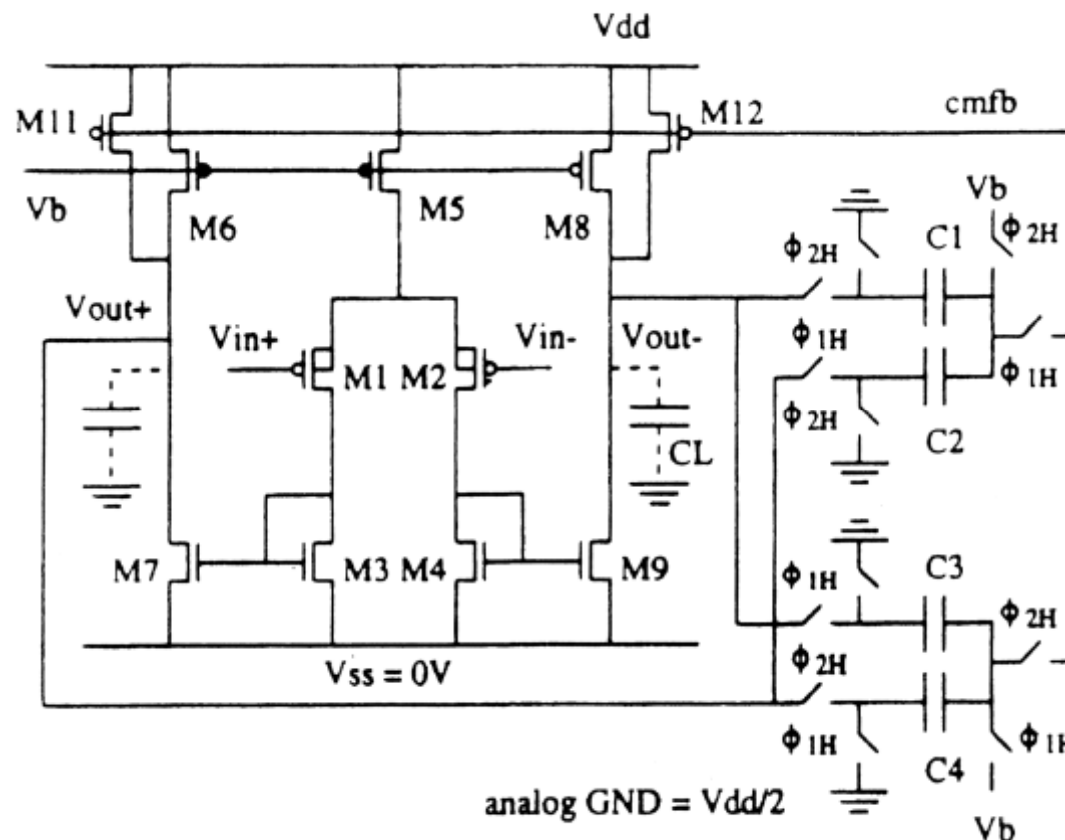


•Transient Response

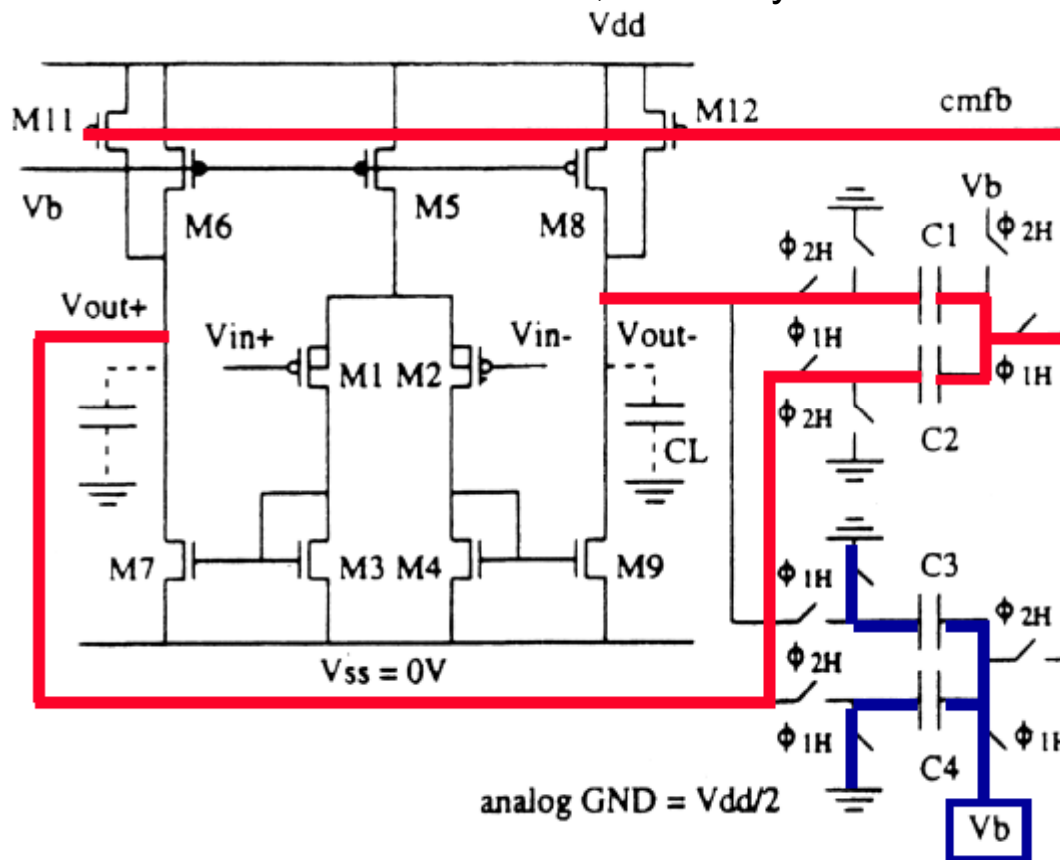


➤ External CM Output Voltage Stabilization Scheme for Discrete-Time Applications

- When a clock is available, as in all sampled data circuitry, it can be used towards a low-power CMFB loop.
- The outputs are measured by a number of switches and capacitors, which provide common-mode feedback to the gates of transistors M11/M12.
- This feedback is not applied directly to the Gates of M8/M6 to make sure that not all current can be switched in the output devices. For common-mode disturbance in the supply lines or substrate, large transients at the outputs can be avoided in this way.



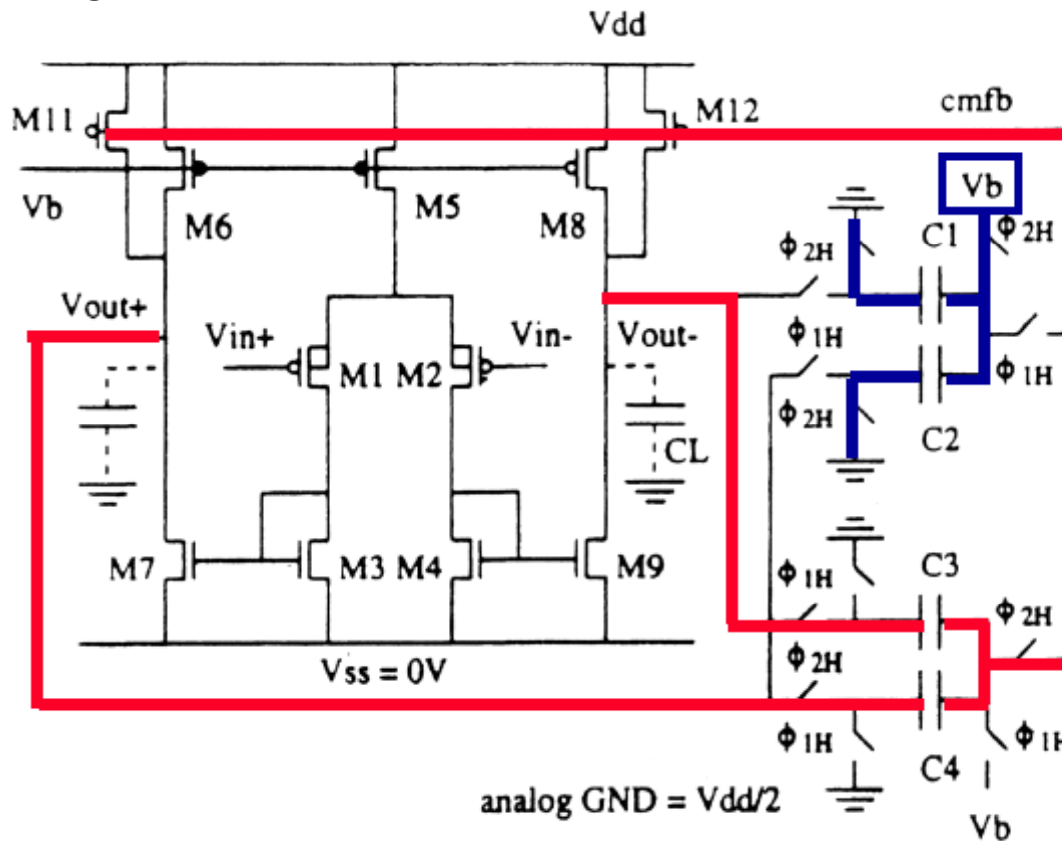
- In order to see how this circuit works, it is copied when all transistors are on, driven by clock W1, and then when all transistors are on, driven by clock W2.



Switches
 ϕ_{1H} closed
 gives **CMFB**
 and
 precharge C

- ✓ In this slide, clock W1 is high, all the transistors, which are driven by this clock, are on. The other ones are off. Thick lines indicate which paths the signals can take. Clearly, the outputs are AC coupled by capacitors C1/C2. Their differential content is then cancelled out. Finally, this signal is then applied to the Gate of transistor M12 to close the feedback loop.
- ✓ The GBW_{CM} is set by gm_{12} and the output load capacitor.
- ✓ The DC level at the Gate of M12 is not defined because of the coupling capacitances C1/C2.

- This is why the other two capacitances $C3/C4$ are precharged to the proper DC voltages.
- Their left side is set to analog ground ($V_{dd}/2$), whereas their right side is set at a biasing voltage, which is the same as at the Gates of current mirror transistors $M5/M6/M8$.
- On the next phase, the capacitors are swapped around, as shown in the next slide. Continuous CMFB is thus ensured.



Switches
 ϕ_{2H} closed
 gives CMFB
 and
 precharge C

- Fully-differential OTA with SC CMFB : ϕ_2
- In the phase ϕ_2 , the other transistors are on. Capacitors $C3/C4$ now provide common-mode feedback, whereas the other ones $C1/C2$ are reset or precharged.

- It is clear that this solution does not take any power at all except for the switching power consumption of all switches and capacitors.
- However, there are a few disadvantages. First of all, the clock frequency appears in the signal path. This is a result of clock injection and charge redistribution, which are typical for all sampled-data circuits such as switched-capacitor filters.
- As a result, we can only use this solution at frequencies well below the clock frequency.
- Moreover, these clock injection and charge redistribution signals severely limit the dynamic range.
- Intermodulation (and folding) of these signals provide an upper limit to the signal-to-noise ratio.
- Finally, the switched capacitors increase the capacitive load of the CMFB amplifier. As a result, the GBW_{CM} will be reduced and the common-mode settling time increased.