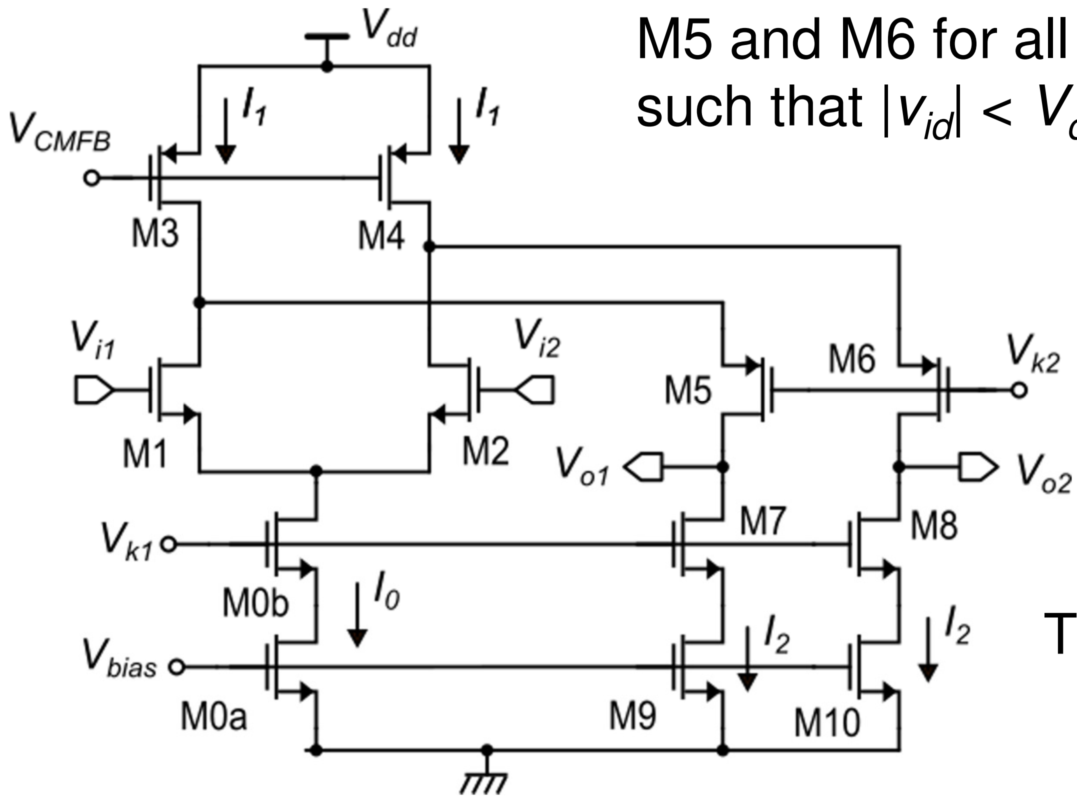
Folded cascode amplifier: quiescent current and total supply current



In order to avoid turning off M5 and M6 for all v_{id} values such that $|v_{id}| < V_{dmax}$ ⇨ $I_1 \geq \max(I_{D1}) = I_0$

We usually choose: $I_1 = I_0$

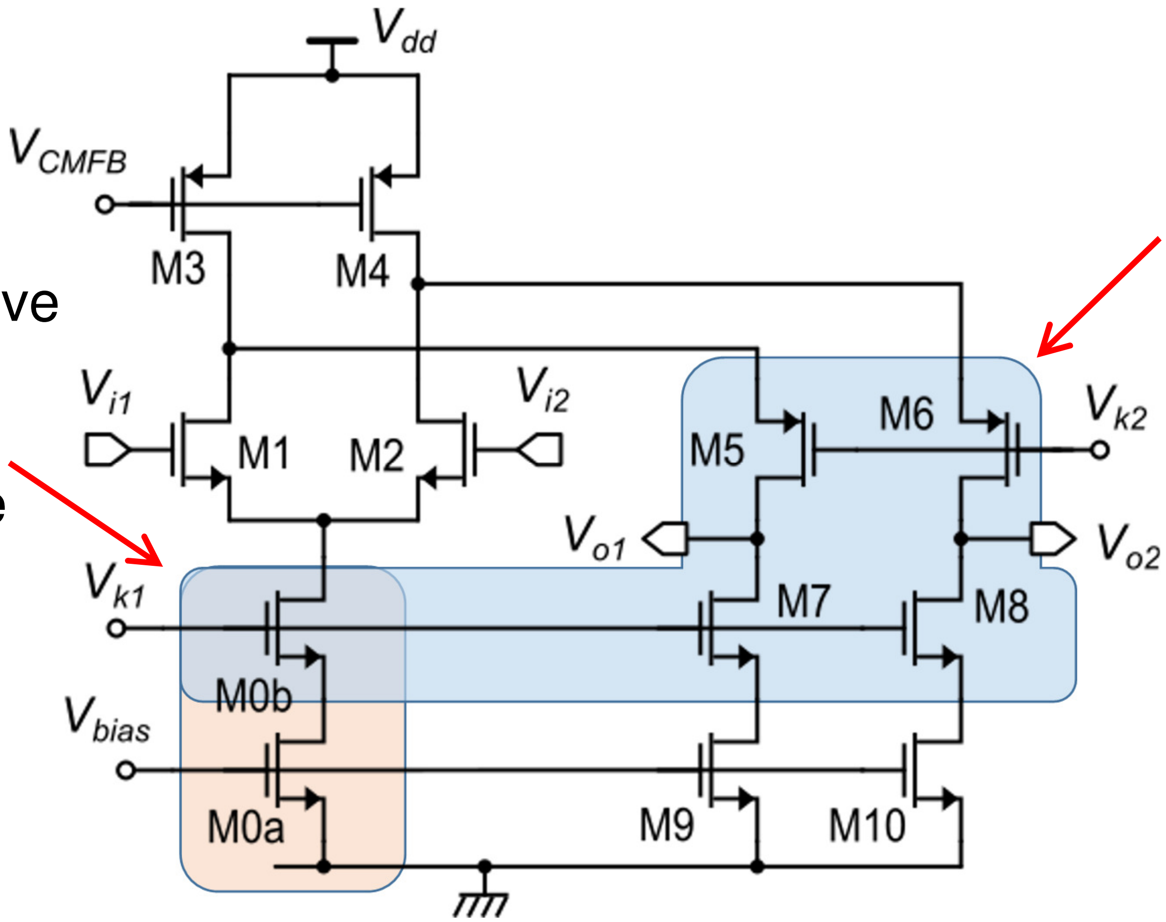
Since it must be: $I_1 - \frac{I_0}{2} - I_2 = 0$

then: $I_2 = \frac{I_0}{2}$

The supply current is: $I_{supply} = 2I_1 = 2I_0$

Folded cascode fully-differential amplifier: noise analysis

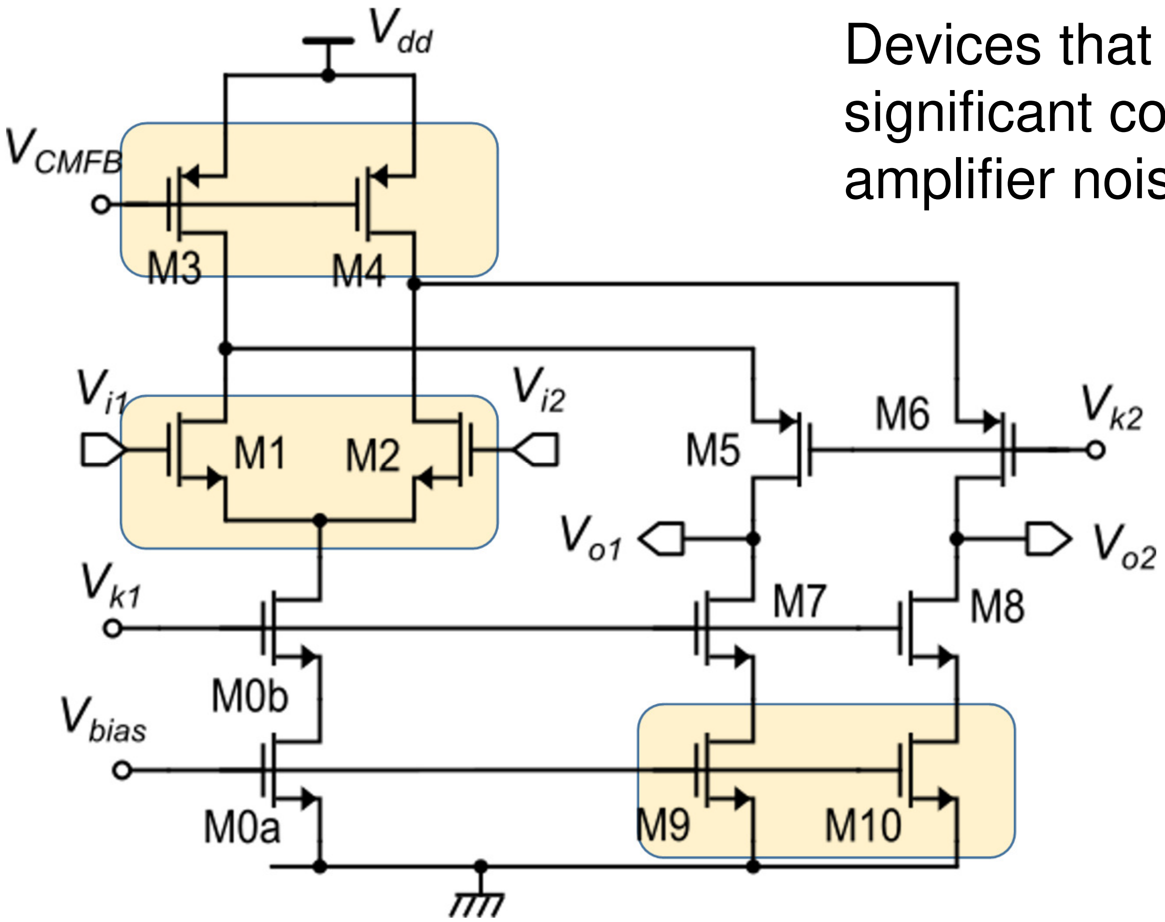
These devices give common mode contributions (except when the amplifier is unbalanced by a large differential input voltage)



All these MOSFET form common gate stages.

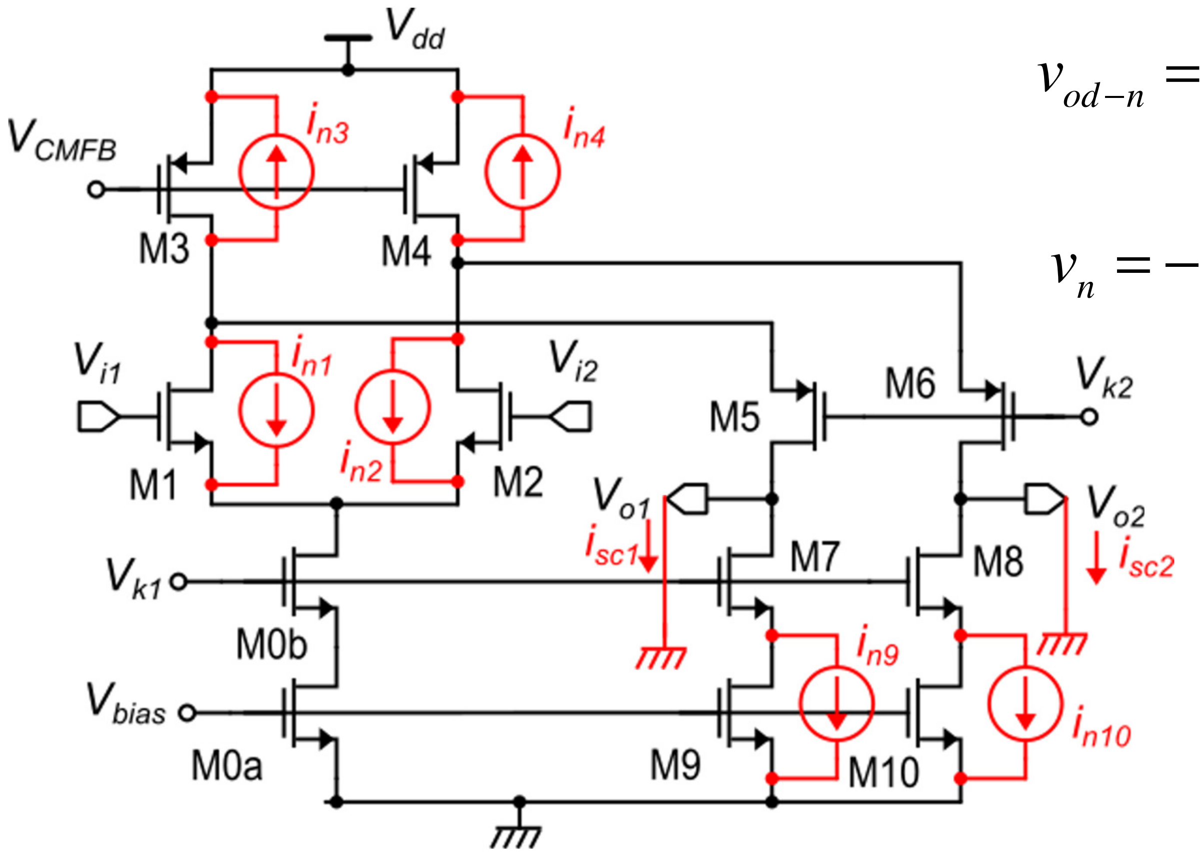
Their noise and offset contribution can be neglected up to relatively high frequencies

Fully-differential amplifier: noise analysis



Devices that gives a significant contribution to the amplifier noise and offset

Calculation of the input referred noise (and offset).



$$v_{od-n} = v_{o2-n} - v_{o1-n} = R_{out}\left(i_{sc2-n} - i_{sc1-n}\right)$$

$$v_n = -\frac{v_{od-n}}{A_{dd}} = -\frac{v_{od-n}}{g_{m1} R_{out}} = \frac{-\left(i_{sc2-n} - i_{sc1-n}\right)}{g_{m1}}$$

$$\begin{cases} i_{sc1-n} = -i_{n3} - i_{n1} - i_{n9} \\ i_{sc2-n} = -i_{n4} - i_{n2} - i_{n10} \end{cases}$$

Calculation of the input referred noise.

$$\begin{cases} i_{sc1-n} = -i_{n3} - i_{n1} - i_{n9} \\ i_{sc2-n} = -i_{n4} - i_{n2} - i_{n10} \end{cases}$$

$$v_n = \frac{-\left(i_{sc2-n} - i_{sc1-n}\right)}{g_{m1}} = \frac{\left(i_{sc1-n} - i_{sc2-n}\right)}{g_{m1}}$$

$$v_n = \frac{\left(i_{n2} - i_{n1}\right) + \left(i_{n4} - i_{n3}\right) + \left(i_{n10} - i_{n9}\right)}{g_{m1}}$$

This expression can be used for both the noise and offset analysis

Noise

$$v_n = \frac{(i_{n2} - i_{n1}) + (i_{n4} - i_{n3}) + (i_{n10} - i_{n9})}{g_{m1}}$$

$$S_{vn} = 2\frac{S_{I1} + S_{I3} + S_{I9}}{g_{m1}^2}$$

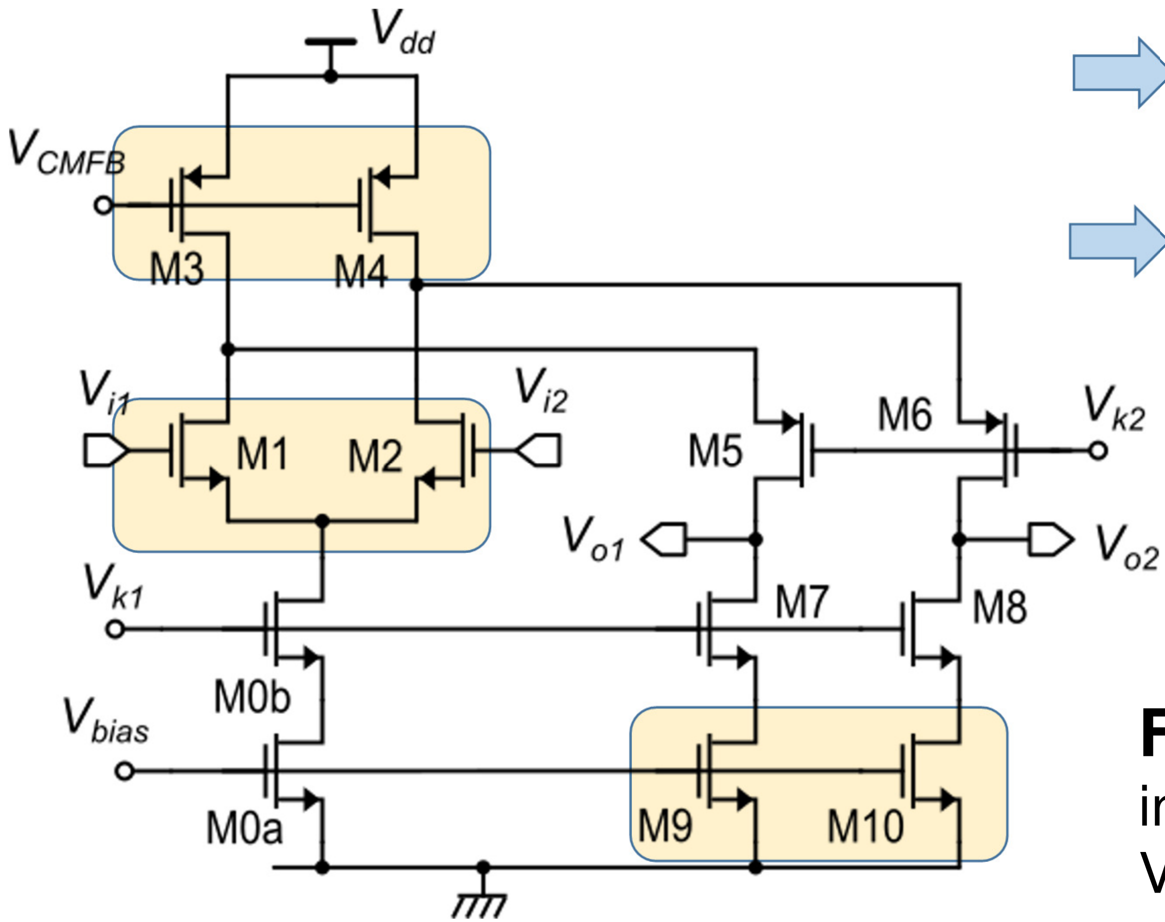
Expressing the S_I as a function of the PSDs of the gate referred voltage noise (S_V)

$$S_{vn} = 2\frac{g_{m1}^2 S_{v1} + g_{m3}^2 S_{v3} + g_{m9}^2 S_{v9}}{g_{m1}^2} = 2\left(S_{v1} + \frac{g_{m3}^2}{g_{m1}^2} S_{v3} + \frac{g_{m9}^2}{g_{m1}^2} S_{v9}\right)$$

$$S_{vn} = 2\left(S_{v1} + F_3^2 S_{v3} + F_9^2 S_{v9}\right)$$

$$\begin{cases} F_3 = \dfrac{g_{m3}}{g_{m1}} = \dfrac{I_{D3}}{I_{D1}} \dfrac{V_{TE1}}{V_{TE3}} \\ F_9 = \dfrac{g_{m9}}{g_{m1}} = \dfrac{I_{D9}}{I_{D1}} \dfrac{V_{TE1}}{V_{TE9}} \end{cases}$$

Fully-differential amplifier: noise analysis



$$
\begin{cases}
F_3 = \dfrac{g_{m3}}{g_{m1}} = \dfrac{I_{D3}}{I_{D1}} \dfrac{V_{TE1}}{V_{TE3}} = 2\dfrac{V_{TE1}}{V_{TE3}} \\
F_9 = \dfrac{g_{m9}}{g_{m1}} = \dfrac{I_{D9}}{I_{D1}} \dfrac{V_{TE1}}{V_{TE9}} = \dfrac{V_{TE1}}{V_{TE9}}
\end{cases}
$$

$$I_{D3} = I_1 = I_0$$

$$I_{D1} = \frac{I_0}{2} \qquad I_{D9} = I_2 = \frac{I_0}{2}$$

F_3 is difficult to make <<1 since it includes a factor of 2 and making V_{TE3} >> V_{TE1} would result in reduced output swing

Thermal noise

$$S_{vn}=2\left(S_{v1}+F_3^2S_{v3}+F_9^2S_{v9}\right)$$

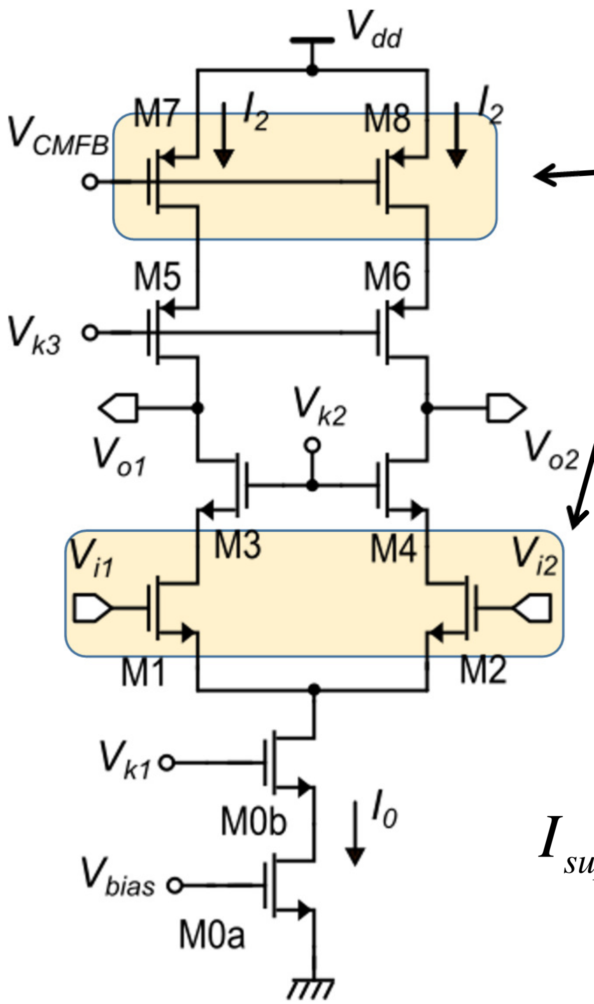
Thermal noise: $$S_{vn}=2\left(\frac{8}{3}kT\frac{1}{g_{m1}}+F_3^2\frac{8}{3}kT\frac{1}{g_{m3}}+F_9^2\frac{8}{3}kT\frac{1}{g_{m9}}\right)$$

$$S_{vn}=2\cdot\frac{8}{3}kT\frac{1}{g_{m1}}\left(1+\frac{g_{m1}}{g_{m3}}F_3^2+\frac{g_{m1}}{g_{m9}}F_9^2\right)=2\cdot\frac{8}{3}kT\frac{1}{g_{m1}}\left(1+F_3+F_9\right)$$

$$g_{m1}=2\cdot\frac{8}{3}kT\frac{1}{S_{vn}}\left(1+F_3+F_9\right)\qquad I_{supply}=2I_0=4I_{D1}=4V_{TE1}g_{m1}$$

$$I_{supply}=4V_{TE1}\cdot2\cdot\frac{8}{3}kT\frac{1}{S_{vn}}\left(1+F_3+F_9\right)$$

A more power-efficient solution: fully differential telescopic amplifier



Only these devices give a significant contribution to noise

$$\begin{cases} i_{sc1-n} = -i_{n1} - i_{n7} \\ i_{sc2-n} = -i_{n2} - i_{n8} \end{cases}$$

$$S_{vni} = 2\left(S_{V1} + F_7^2 S_{V7}\right)$$

$$v_n = \frac{\left(i_{n2} - i_{n1}\right) + \left(i_{n8} - i_{n7}\right)}{g_{m1}}$$

$$F_7 = \frac{g_{m7}}{g_{m1}} = \frac{I_{D7}}{I_{D1}}\frac{V_{TE1}}{V_{TE7}} = \frac{V_{TE1}}{V_{TE7}}$$

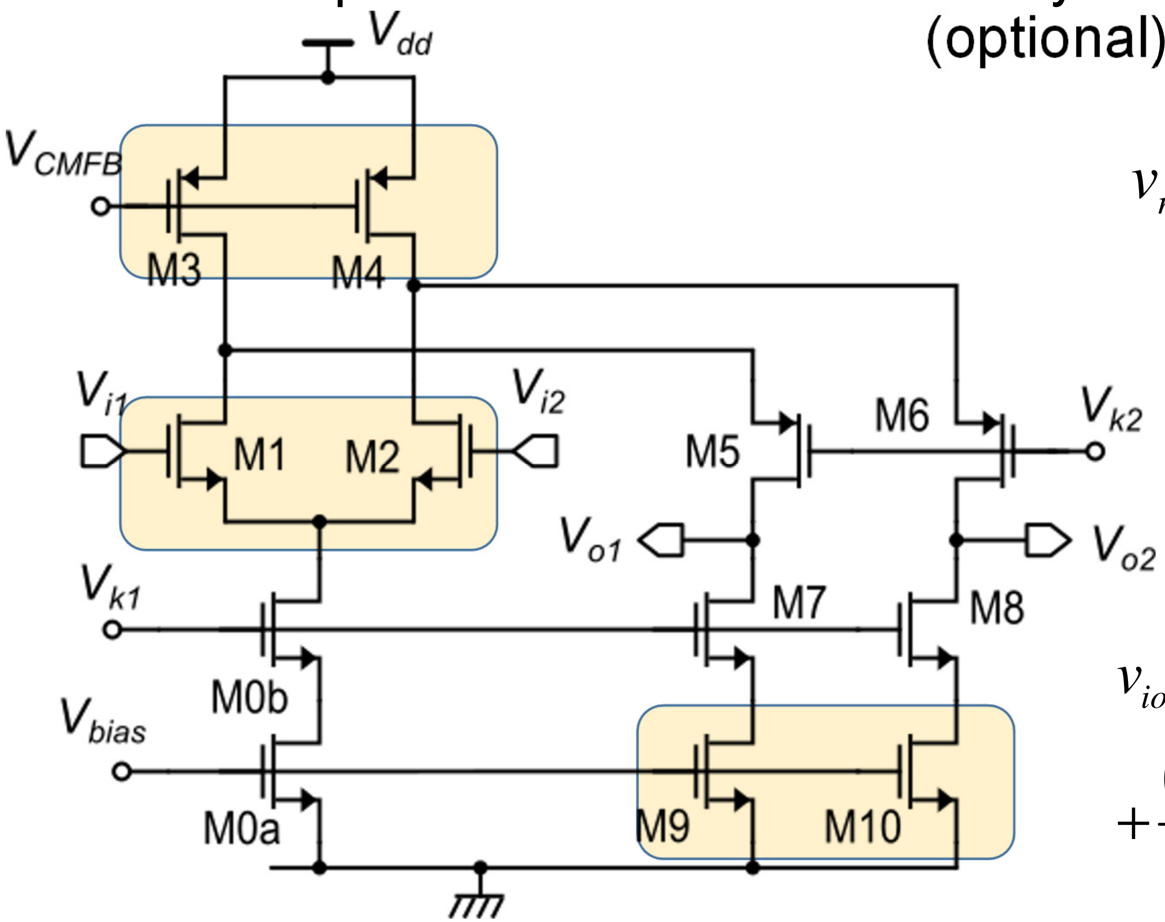
Compared with the folded cascode

$$S_{Vn-th} = 2 \cdot \frac{8}{3} kT \frac{1}{g_{m1}}\left(1 + F_7\right)$$ (less noise for the same g_{m1})

$$I_{supply} = I_0 = 2I_{D1} = 2g_{m1}V_{TE1}$$ (half the current for the same g_{m1})

(... but also much smaller input and output ranges)

Input referred offset of the fully-differential Folded Cascode (optional)



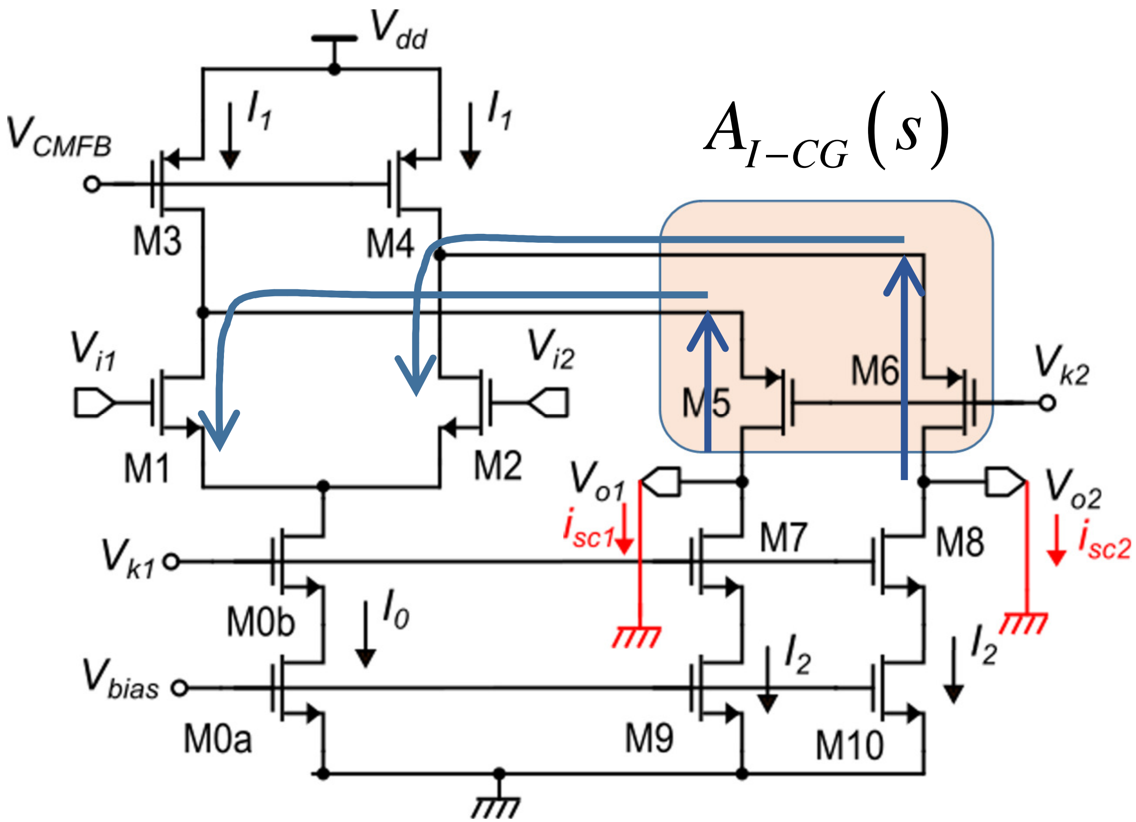
$$v_n = \frac{(i_{n2} - i_{n1}) + (i_{n4} - i_{n3}) + (i_{n10} - i_{n9})}{g_{m1}}$$

$$v_{io} = \frac{\Delta I_{D2,1} + \Delta I_{D4,3} + \Delta I_{D10,9}}{g_{m1}}$$

$$v_{io} = \Delta V_{2,1} + F_3 \Delta V_{4,3} + F_9 \Delta V_{10,9} + \\ + \frac{(V_{GS} - V_t)_1}{2} \left(\frac{\Delta \beta_{2,1}}{\beta_1} + \frac{I_{D3}}{I_{D1}} \frac{\Delta \beta_{4,3}}{\beta_3} + \frac{I_{D9}}{I_{D1}} \frac{\Delta \beta_{10,9}}{\beta_9} \right)$$

$\frac{I_{D3}}{I_{D1}} \cong 2$ $\frac{I_{D9}}{I_{D1}} \cong 1$

Frequency response of the folded cascode op-amp

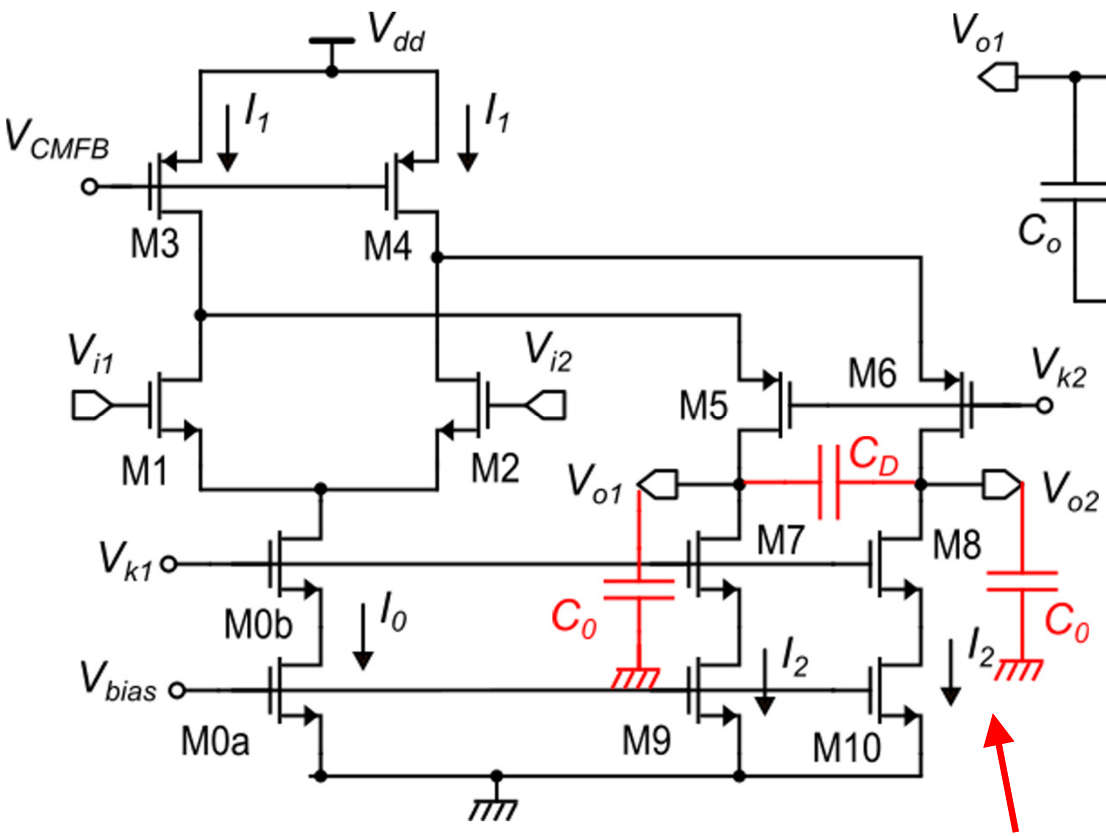


Let us analyze the frequency response of the output short circuit currents.

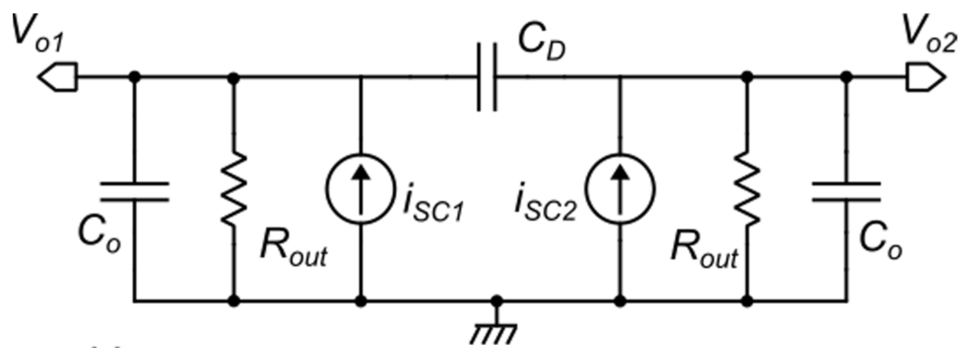
The drain current variations produced by the input pair reach the output port passing through the common gate stage

Let us indicate the transfer function of the common gate as $A_{I\text{-}CG}(s)$

Frequency response of the folded cascode op-amp



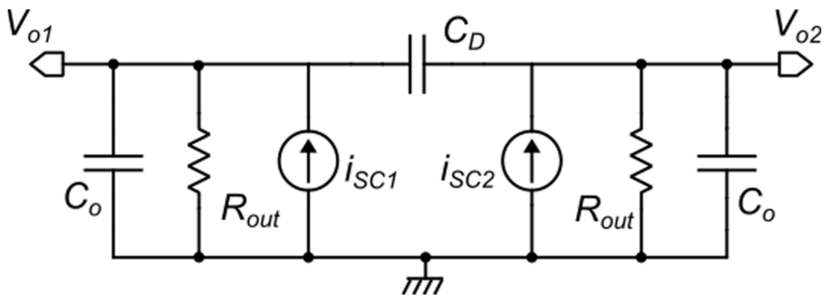
C_O, C_D: Load capacitances

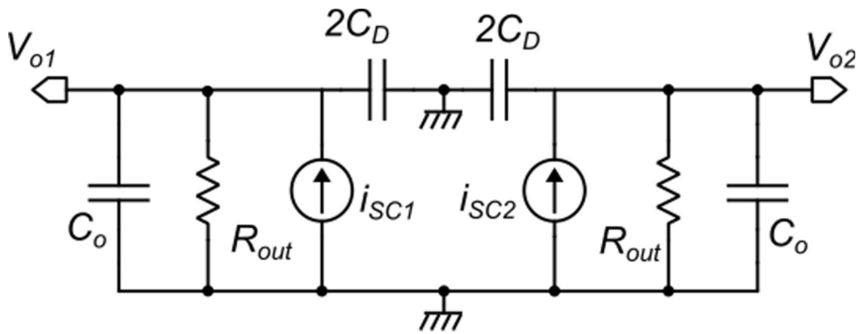


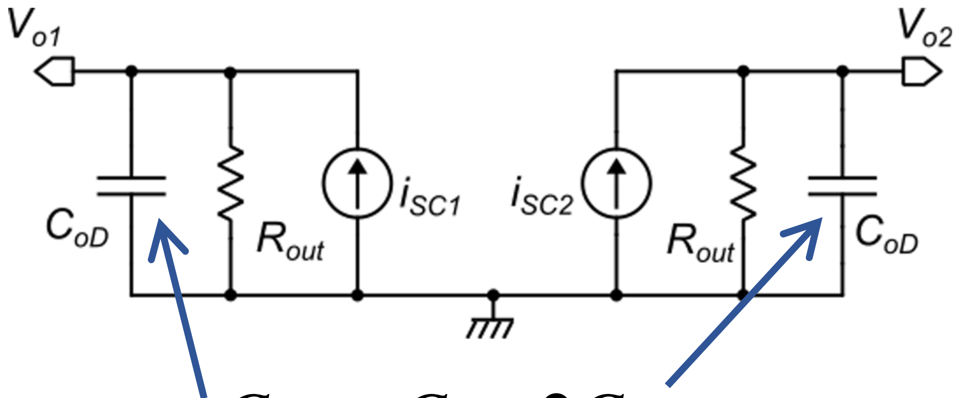
Small signal circuit of the output ports

$$\begin{cases} i_{sc1} = \left(-g_{m1}\dfrac{v_{id}}{2}\right) A_{I-CG}(s) \\ i_{sc2} = \left(g_{m1}\dfrac{v_{id}}{2}\right) A_{I-CG}(s) \end{cases}$$

Differential mode analysis

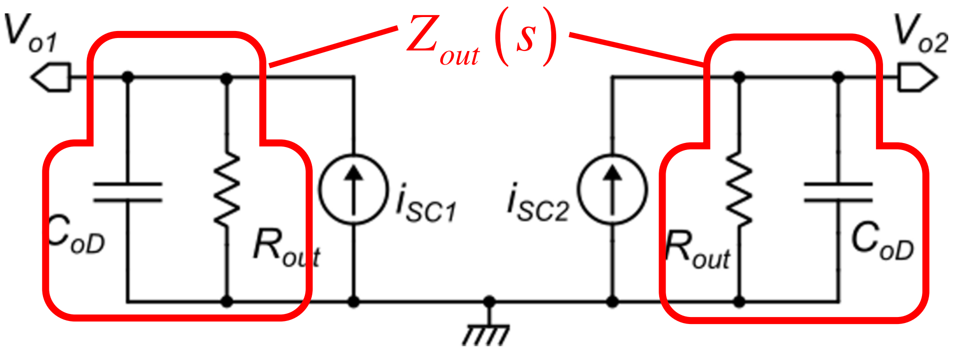






$$C_{oD} = C_o + 2C_D$$

Differential mode analysis



$$\begin{cases} i_{sc1} = \left(-g_{m1}\dfrac{v_{id}}{2}\right)A_{I-CG}(s) \\ i_{sc2} = \left(g_{m1}\dfrac{v_{id}}{2}\right)A_{I-CG}(s) \end{cases}$$

$$v_{od} = (i_{sc2} - i_{sc1})Z_{out}(s)$$

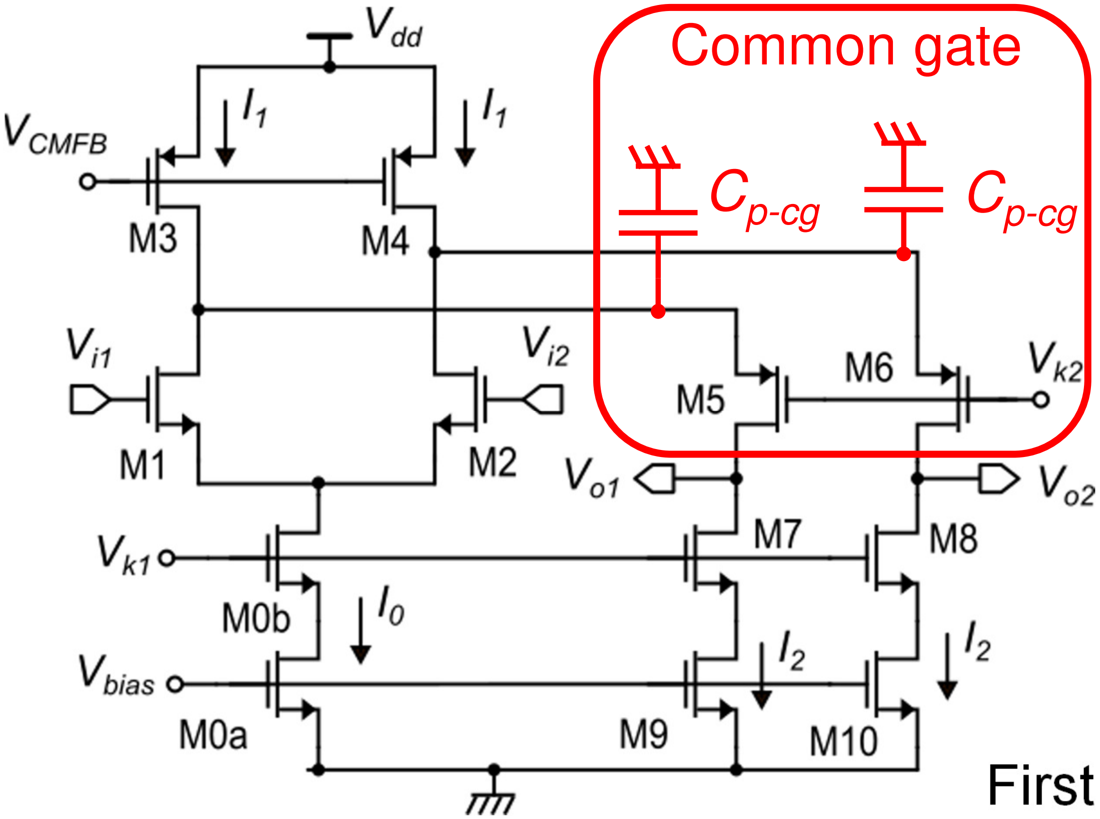
$$v_{od} = g_{m1}v_{id}A_{I-CG}(s)R_{out}\frac{1}{1+sC_{oD}R_{out}}$$

$$Z_{out}(s) = \frac{1}{\dfrac{1}{R_{out}} + sC_{oD}} = \frac{R_{out}}{1+sC_{oD}R_{out}}$$

$$A_{I-CG}(s) \cong \frac{1}{1+\dfrac{s}{\omega_{pCG}}}$$

Response of the common gate

Differential mode analysis



$$v_{od} = g_{m1} v_{id} A_{I-CG}(s) R_{out} \frac{1}{1 + sC_{oD} R_{out}}$$

$$A_{dd}(s) = g_{m1} R_{out} \frac{1}{\left(1 + \frac{s}{\omega_{pCG}}\right)} \cdot \frac{1}{\left(1 + \frac{s}{\omega_{pd}}\right)}$$

$A_{dd}(0)$

Dominant pole: $\omega_{pd} = \frac{1}{C_{oD} R_{out}}$

First non dominant pole: $\omega_{pCG} = \frac{g_{m5}}{C_{p-cg}} \cong \frac{g_{m5}}{C_{gs5}} \cong f_{T5}$

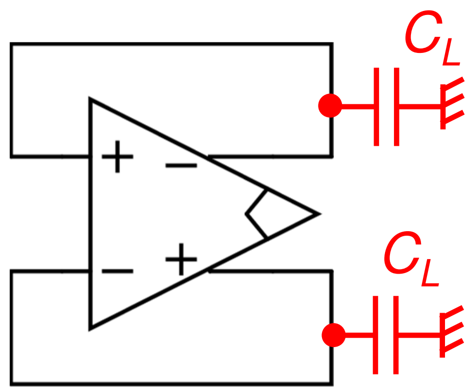
Differential mode analysis: stability in closed loop configurations

Unity gain angular-frequency:

$$\omega_{0d} = \omega_{pd} A_{dd}(0)$$

$$\omega_{pd} = \frac{1}{C_{oD} R_{out}}$$

$$\omega_{0d} = \frac{g_{m1} R_{out}}{C_{oD} R_{out}} = \frac{g_{m1}}{C_{oD}}$$



Unity gain case with only load capacitance to gnd

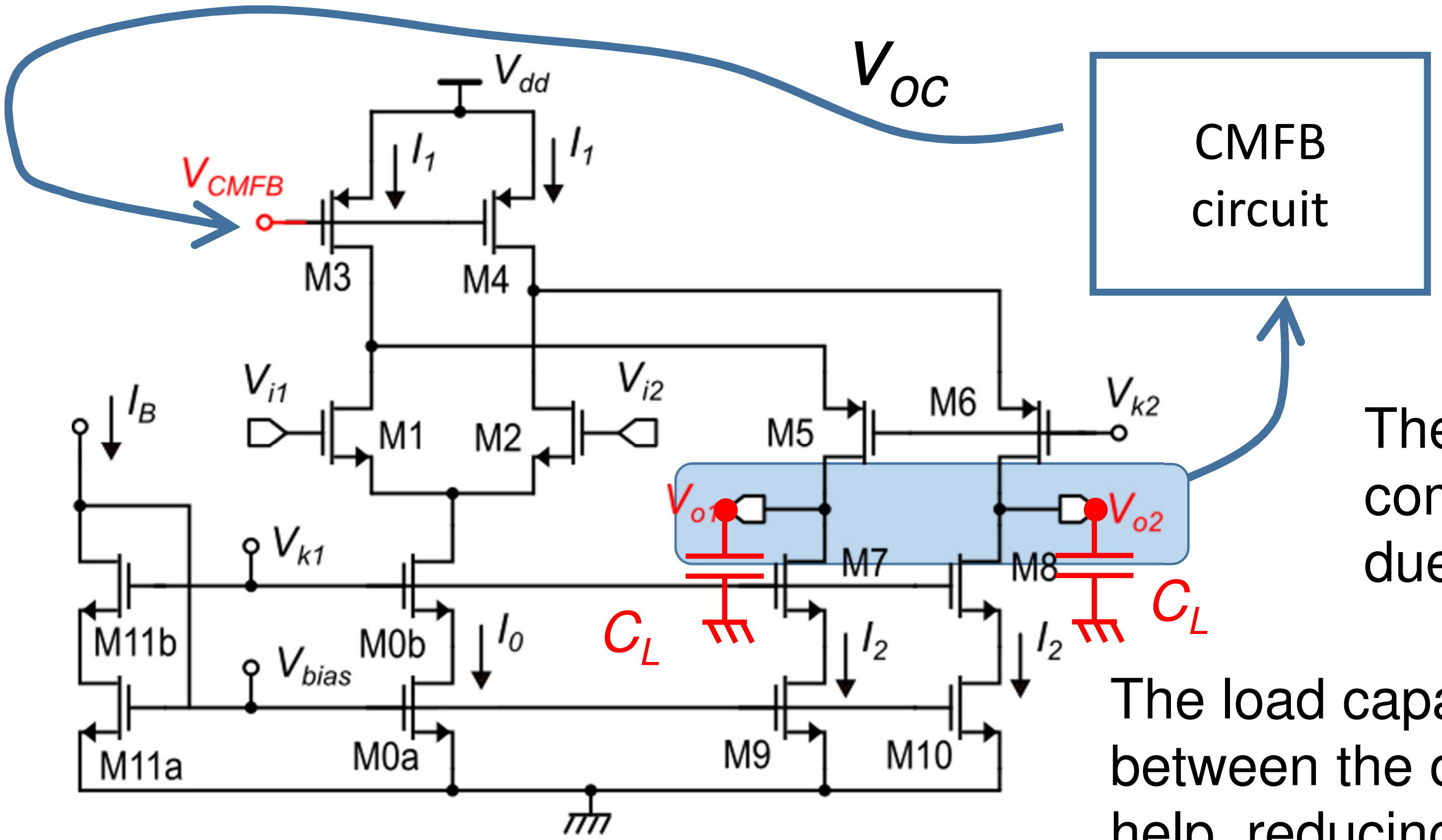
$$C_{oD} \cong C_L$$

First non dominant pole: $\omega_2 = \omega_{pCG} \cong \dfrac{g_{m5}}{C_{gs5}}$

To have about 70° phase margin: $\omega_2 = 3\omega_{0d}$

Increasing the equivalent load capacitances (C_L) reduces the unity gain angular frequency (ω_{0d}), improving the phase margin but also reduces the GBW.

Mention to common mode stability



Considering small signal components, this is a feedback loop that can lead to instability

The dominant pole of the common mode loop is still due to the output capacitance

The load capacitances, if connected between the outputs and ground, help reducing the 0-dB frequency of the CMFB loop, improving stability

An open-loop, fully-differential instrumentation amplifier

Due to the local feedback loops formed by A1-M1 and A2-M2

$$V_{S1} \cong V_{i1}, \quad V_{S2} \cong V_{i2}$$

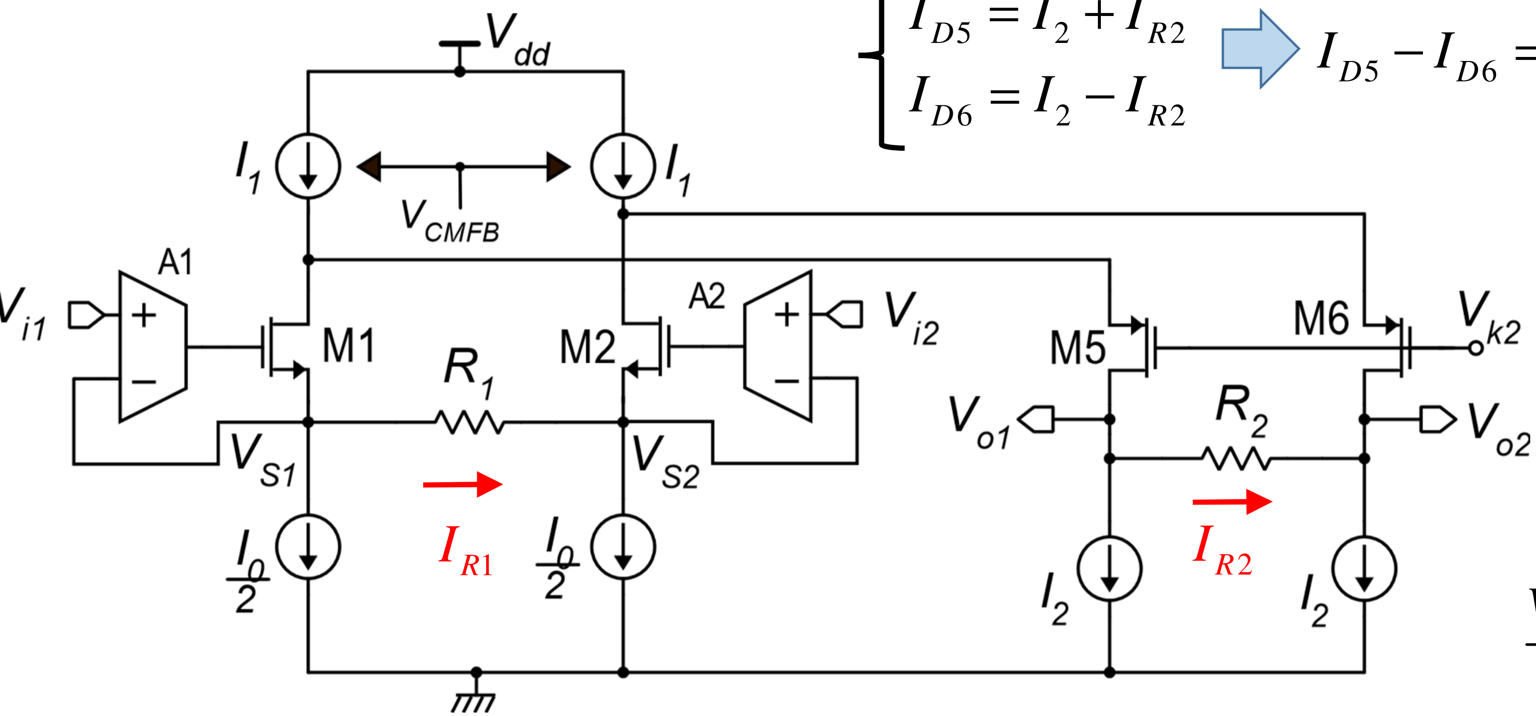
$$I_{R1} = \frac{V_{S1} - V_{S2}}{R_1} \cong \frac{V_{id}}{R_1}$$

$$\begin{cases} I_{D1} = \dfrac{I_0}{2} + I_{R1} \\ I_{D2} = \dfrac{I_0}{2} - I_{R1} \end{cases}$$

$$I_{D1} - I_{D2} = 2I_{R1}$$

$$\begin{cases} I_{D5} = I_2 + I_{R2} \\ I_{D6} = I_2 - I_{R2} \end{cases}$$

$$I_{D5} - I_{D6} = 2I_{R2}$$



$$\begin{cases} I_{D5} = I_1 - I_{D1} \\ I_{D6} = I_1 - I_{D2} \end{cases}$$

$$I_{D5} - I_{D6} = I_{D2} - I_{D1} = 2I_{R1}$$

$$2I_{R2} = -2I_{R1}$$

$$\frac{V_{od}}{R_2} = -\frac{V_{id}}{R_1}$$

$$V_{od} = -V_{id}\frac{R_2}{R_1}$$