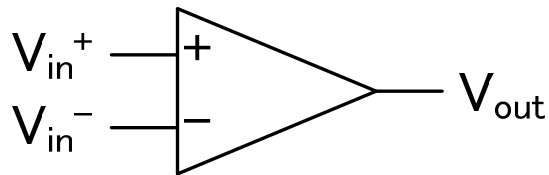


13. Full-differential operational amplifier

Kanazawa University
Microelectronics Research Lab.
Akio Kitagawa

13.1 The foundations of Full-differential OPA

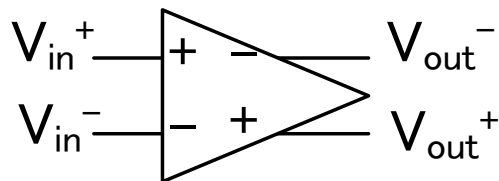
Function of a full-differential OPA



Symbol of Single-end OPA

Function

$$\left\{ \begin{array}{l} V_{out} = A_d (V_{in}^+ - V_{in}^-) \\ A_d = \text{Differential Gain} \end{array} \right.$$



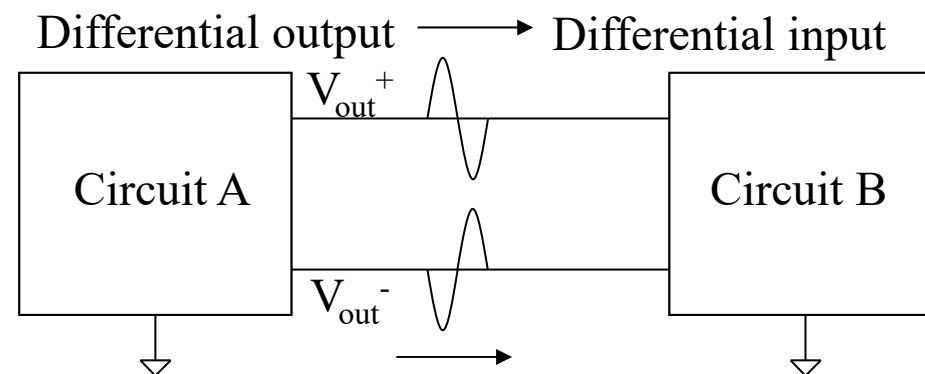
Symbol of Full-differential

$$\left\{ \begin{array}{l} V_{out}^+ = \frac{A_d}{2} (V_{in}^+ - V_{in}^-) \\ V_{out}^- = -\frac{A_d}{2} (V_{in}^+ - V_{in}^-) \\ V_{out} = V_{out}^+ - V_{out}^- \end{array} \right.$$

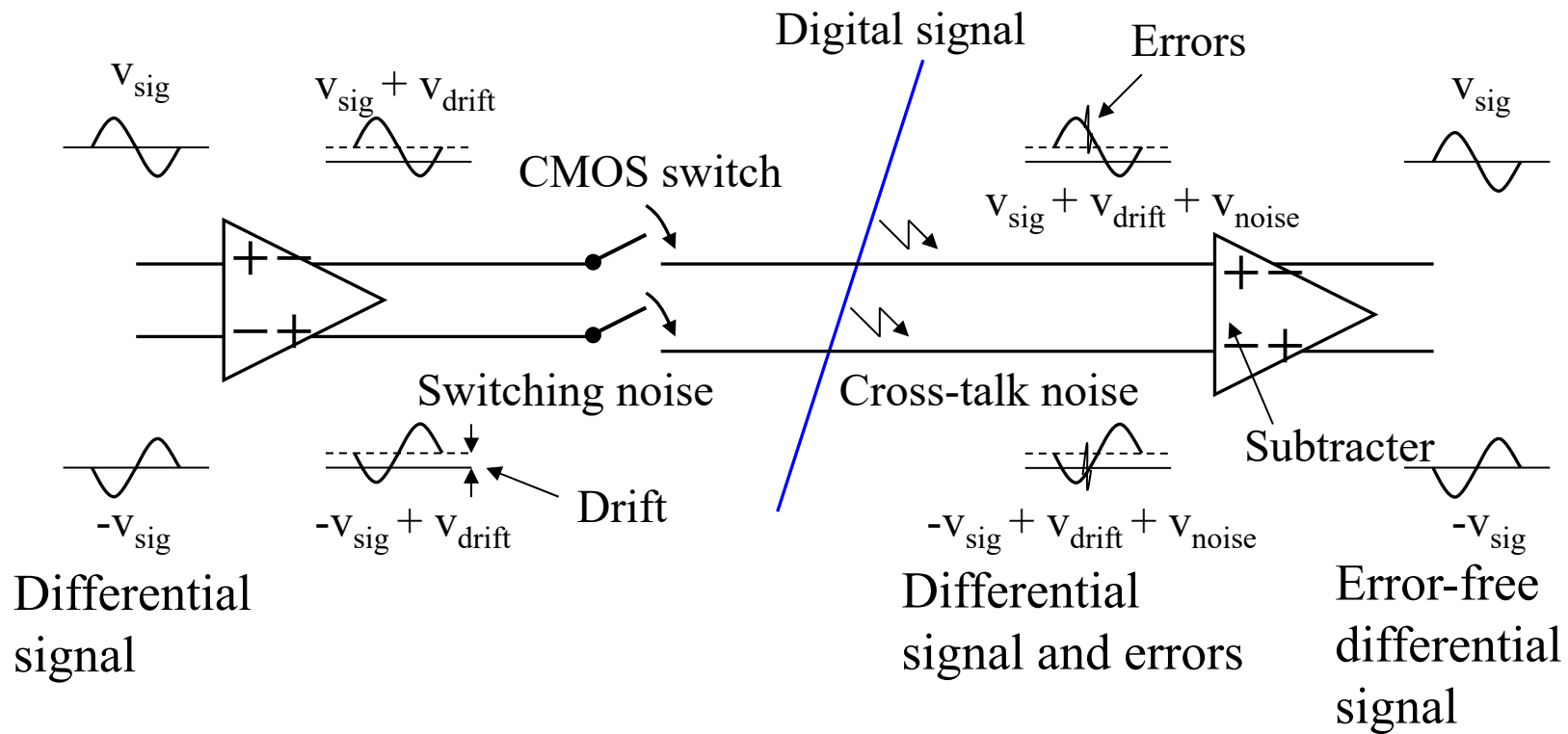
$A_d = \text{Differential Gain}$

Advantages of full-differential OPA

- Feature of full-differential OPAs
 - Cancellation of common-mode noise
 - Cancellation of clock feedthrough and charge injection error (essential for the discrete analog circuit)
 - Cancellation of even-order distortions of MOSFET



Cancellation of common-mode noise

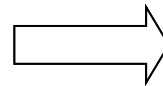


Drift : A slow shift of the common-mode voltage is often observed as a drift. The drift error occurs by a temperature change easily.

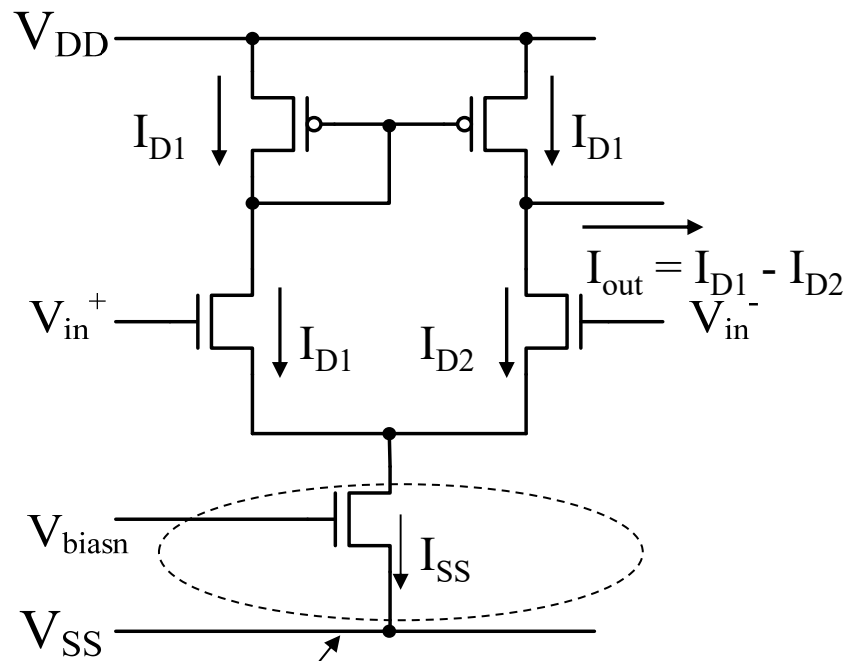
Circuit configuration of diff. amp.

Gain = 1/2 times lower for each output port and mirror symmetry

Current mirror load

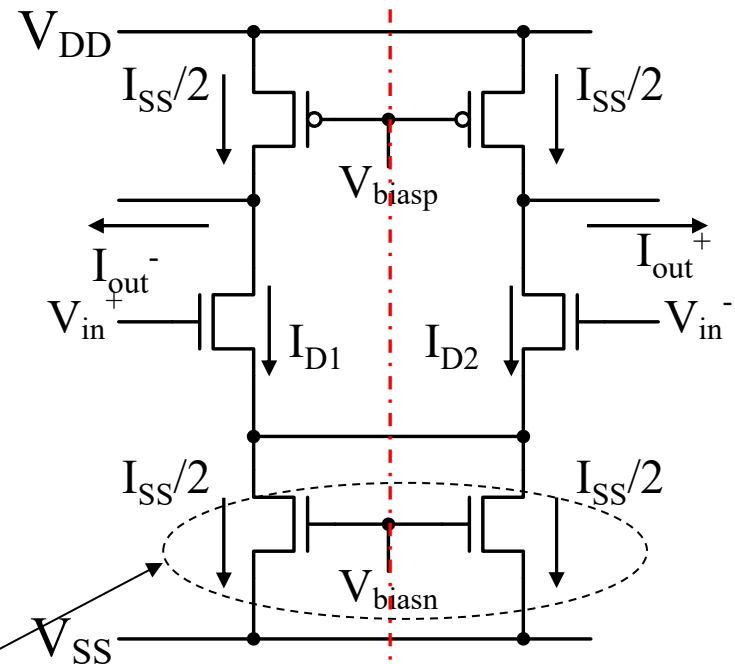


Current source load



common mode rejection

Current subtraction



Mirror symmetry

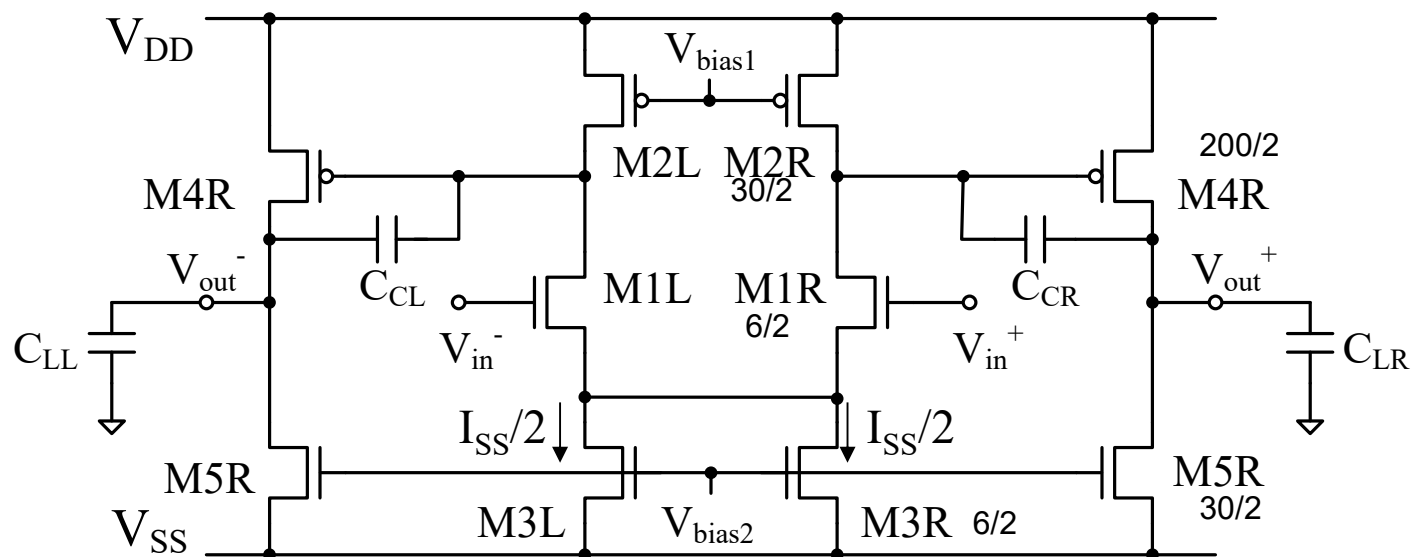
$$I_{SS}/2 = (I_{D1} + I_{D2})/2$$

$$I_{out}^+ = I_{SS}/2 - I_{D2} = (I_{D1} - I_{D2})/2$$

$$I_{out}^- = I_{SS}/2 - I_{D1} = (I_{D2} - I_{D1})/2$$

13.2 2-stage CS OPA

2-stage CS full-differential OPA



$$SR = \frac{I_{SS}}{C_C}$$

$$G_0 = g_{m1}(r_{ds1} // r_{ds2}) \cdot g_{m4}(r_{ds4} // r_{ds5})$$

$$\omega_{p1} = \frac{1}{g_{m4}(r_{ds1} // r_{ds2}) \cdot (r_{ds4} // r_{ds5}) \cdot C_C}$$

$$\omega_{p2} = \frac{g_{m4}}{C_L}$$

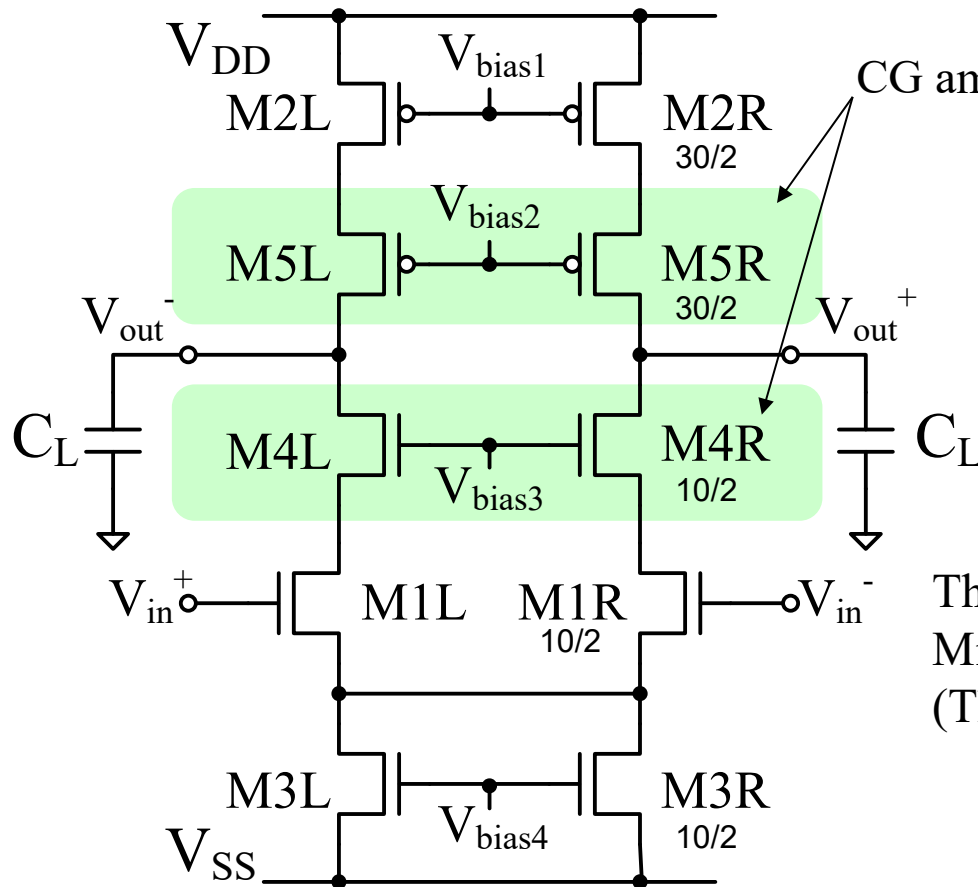
$$\omega_u = \frac{g_{m1}}{C_C}$$

CMRR	○
PSRR	△
Gain	△
Bandwidth, SR	×
Power	△

NOTE: GBP increases with increasing g_{m1} , but power consumption is increased with the g_{m1} ($g_m \propto I_{DS}^{0.5}$).

13.3 Cascode OPA

Characteristic of cascode OPA



The bias current of M1 and M2 is reused for the M4 and M5.

CG amplifier

$$SR = \frac{I_{SS}}{C_L}$$

$$G_0 = g_{m1} \cdot (g_{m4} \cdot r_{ds4} \cdot r_{ds1}) // (g_{m5} \cdot r_{ds5} \cdot r_{ds2})$$

$$\omega_{p1} = \frac{1}{(g_{m4} \cdot r_{ds4} \cdot r_{ds1}) // (g_{m5} \cdot r_{ds5} \cdot r_{ds2}) \cdot C_L}$$

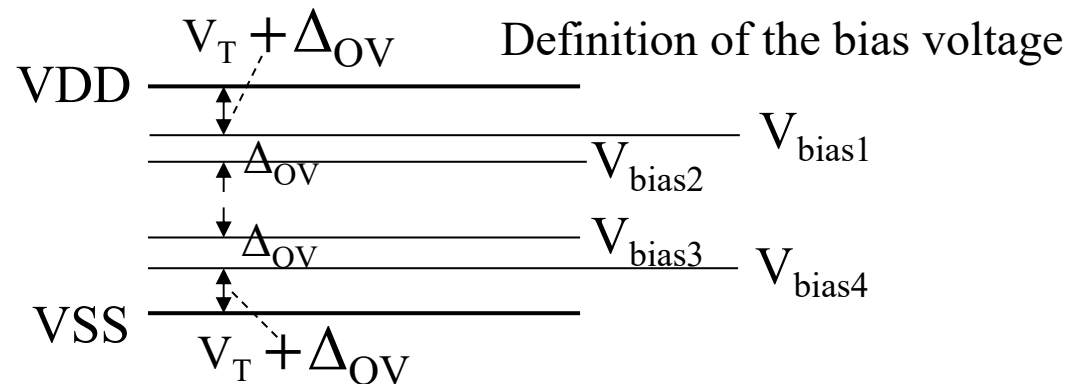
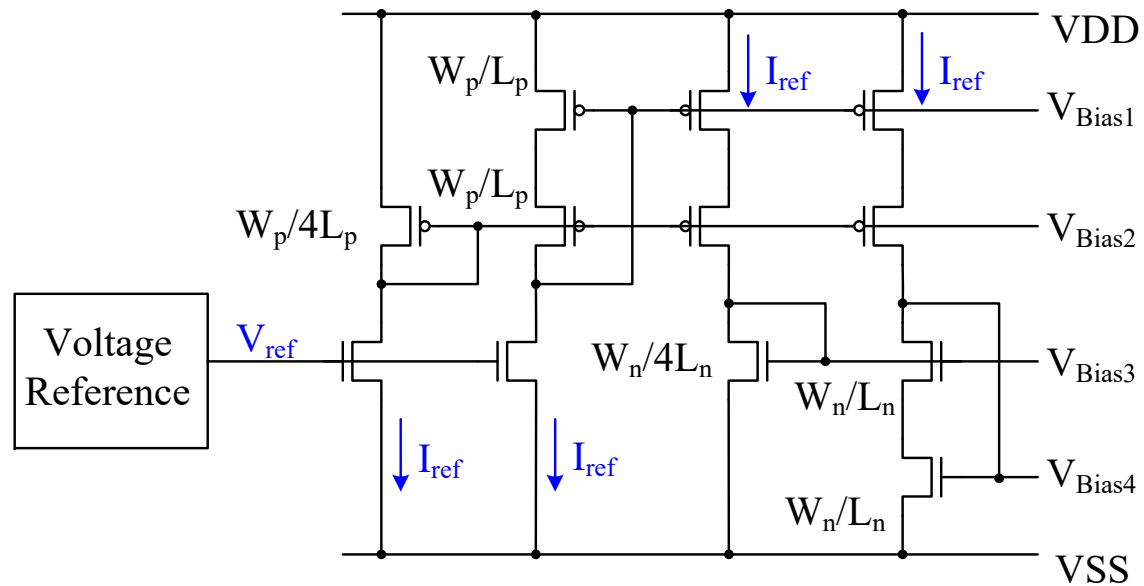
$$\omega_u = \frac{g_{m1}}{C_L}$$

The voltage gain of M1 is about unity and the Miller effect is negligible, thus, $\omega_{p2} \cong \omega_u$
(The Phase margin depends on the C_L .)

CMRR	○
PSRR	○
Gain	○
Bandwidth, SR	○ (depends on C_L)
Power	○

Cascode bias circuit

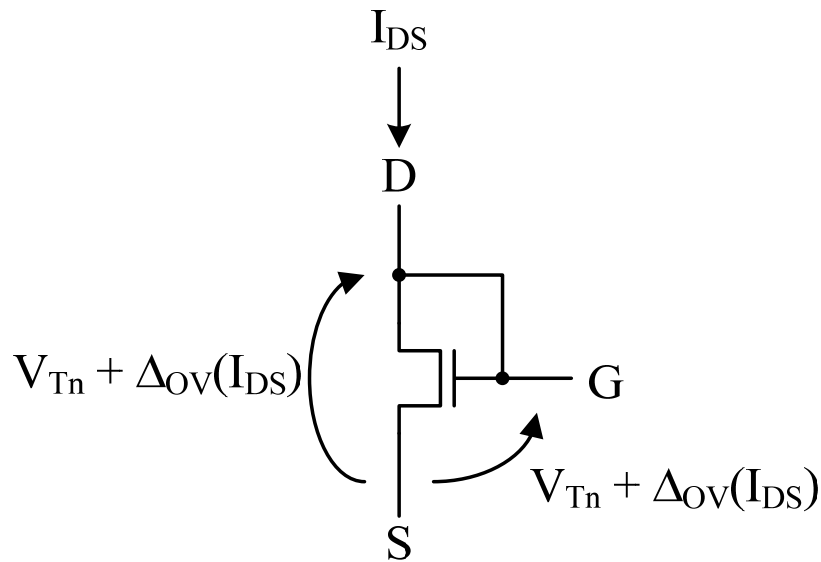
See Chapter 4, Wide Swing cascode current mirror.



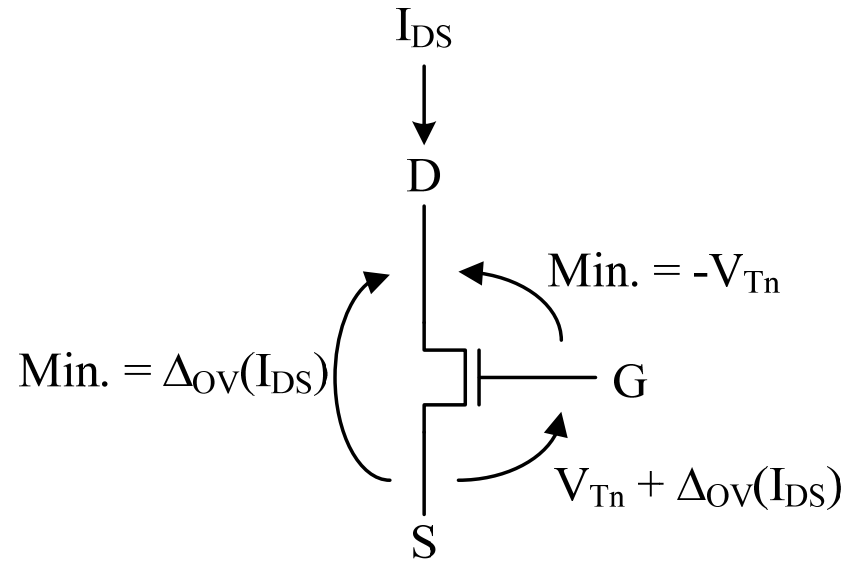
13.4 Folded cascode OPA

NOTE: The folded cascode OPA consumes larger bias current, but it has some advantages, such as wide input range, good stability, high gain, which these features are **suitable for IP**.

Calculation method of the common-mode range (remind)

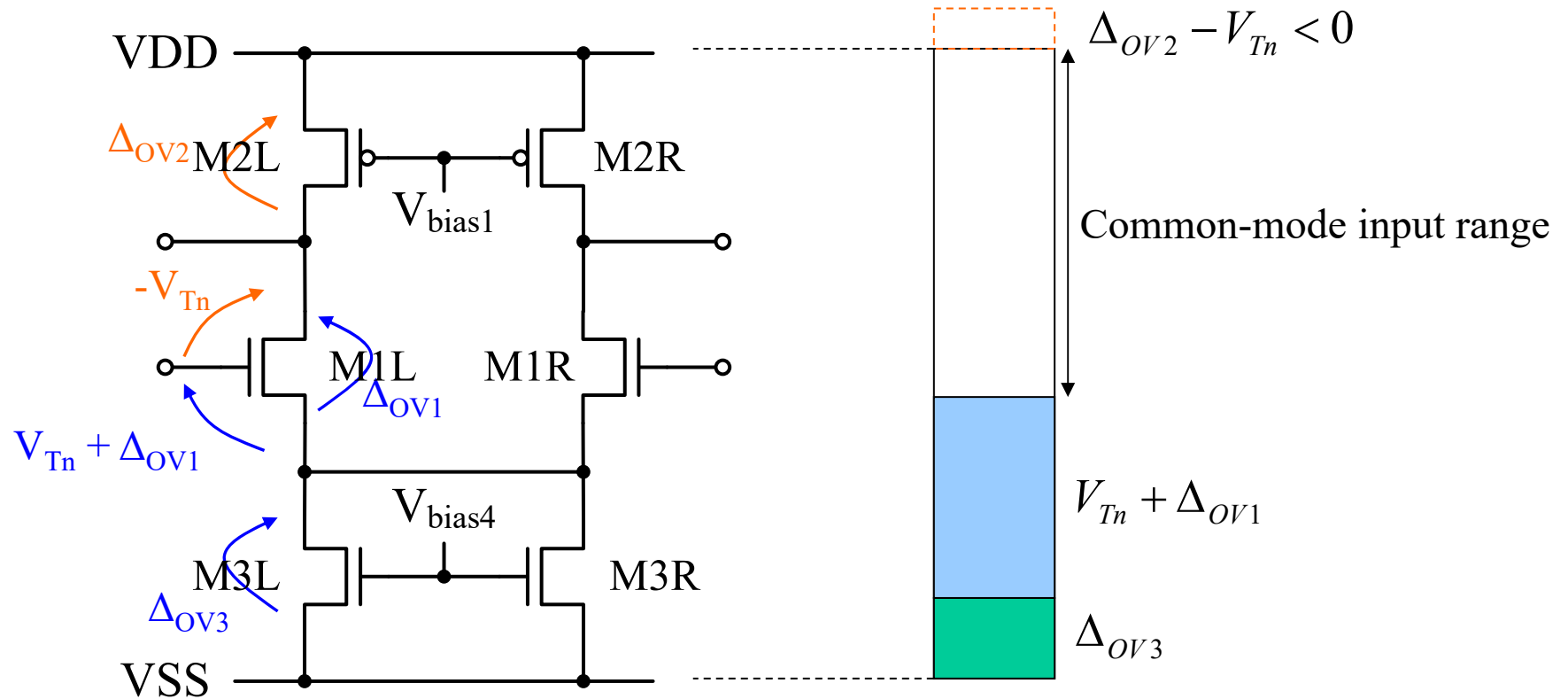


$$V_{DS} = V_{GS}$$

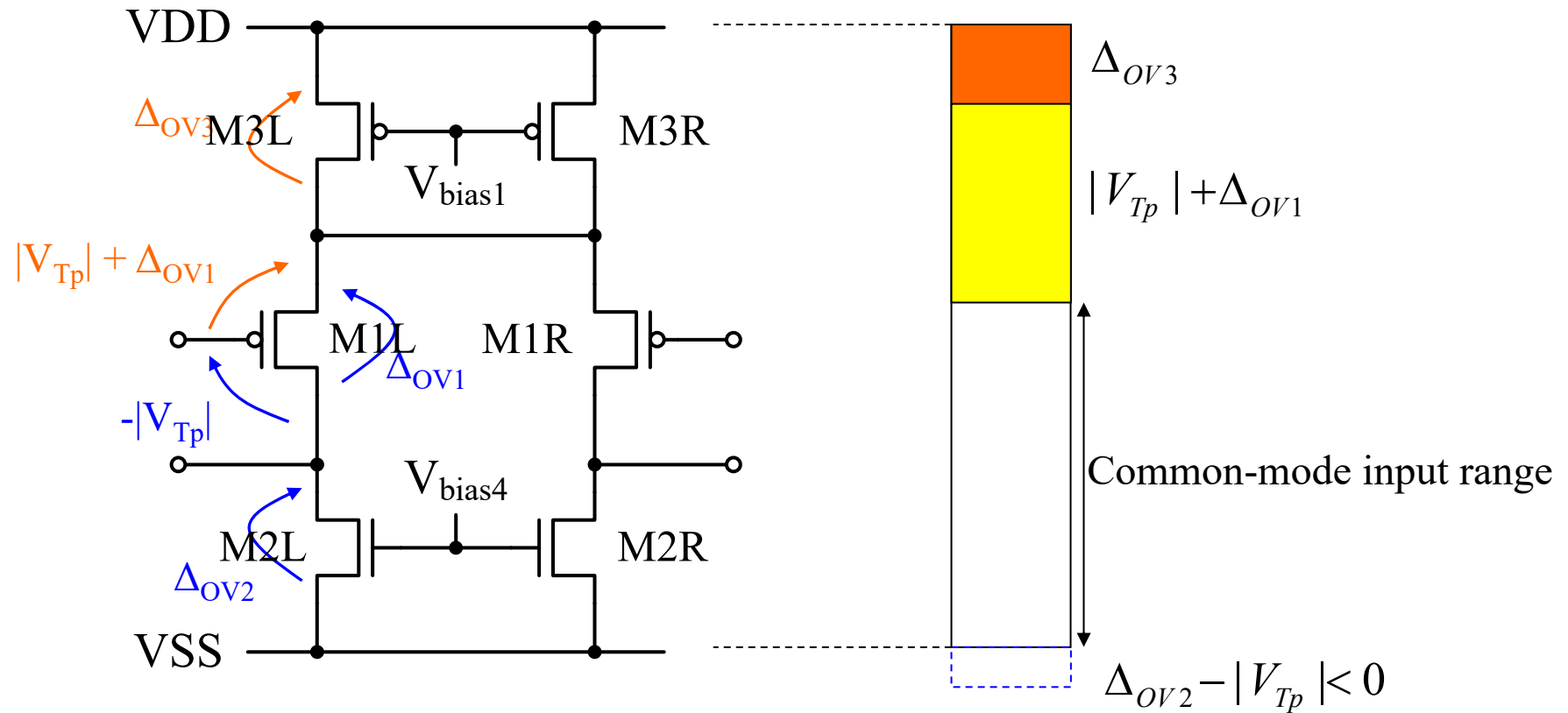


$$V_{DS} \neq V_{GS}$$

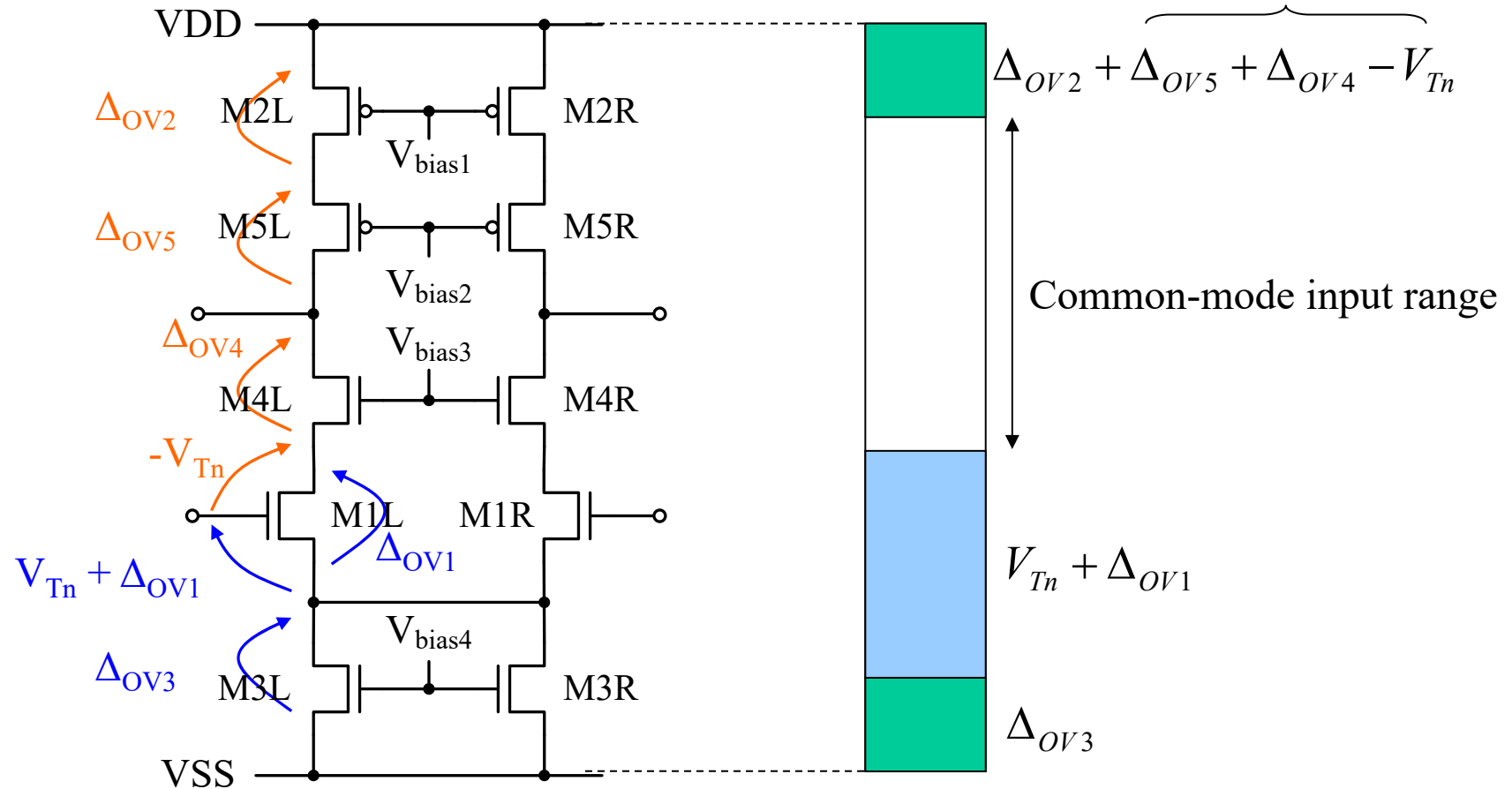
Common-mode input range of n-ch input differential amplifier



Common-mode input range of p-ch input differential amplifier



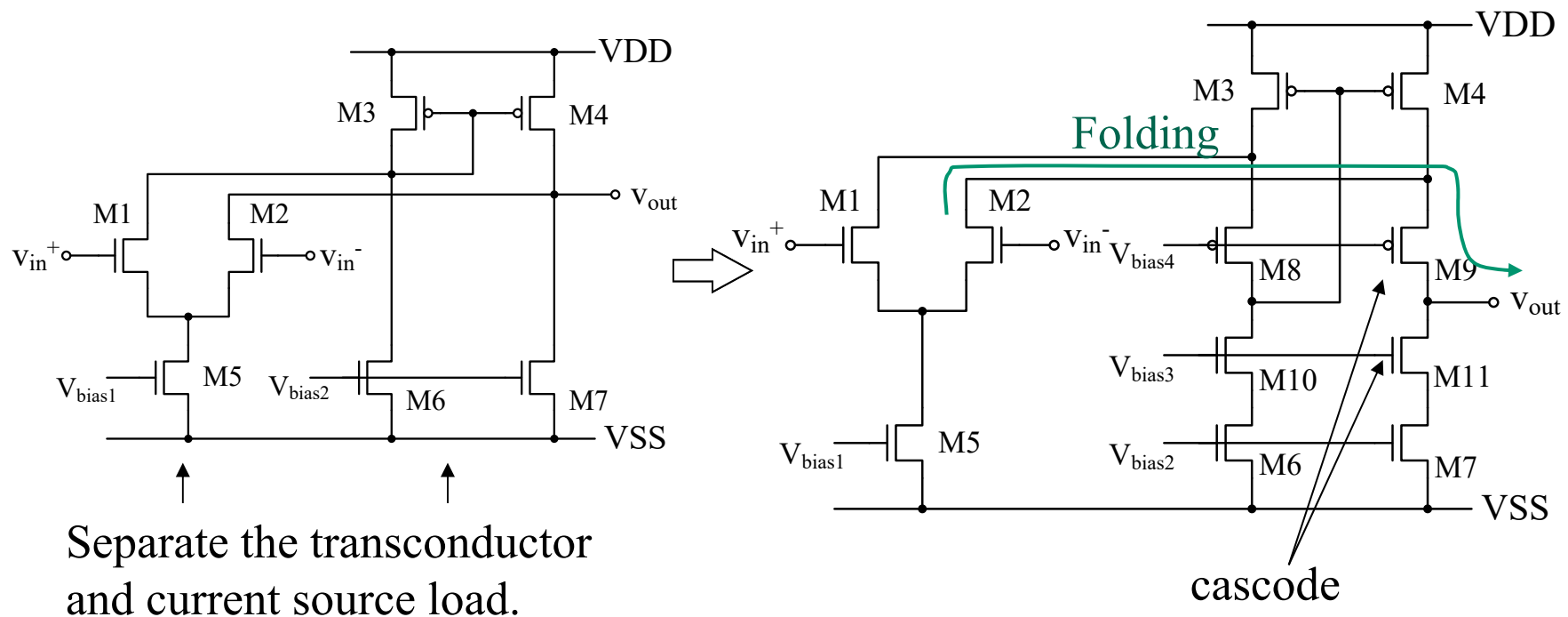
Common-mode input range of n-ch input differential amplifier ~ 0



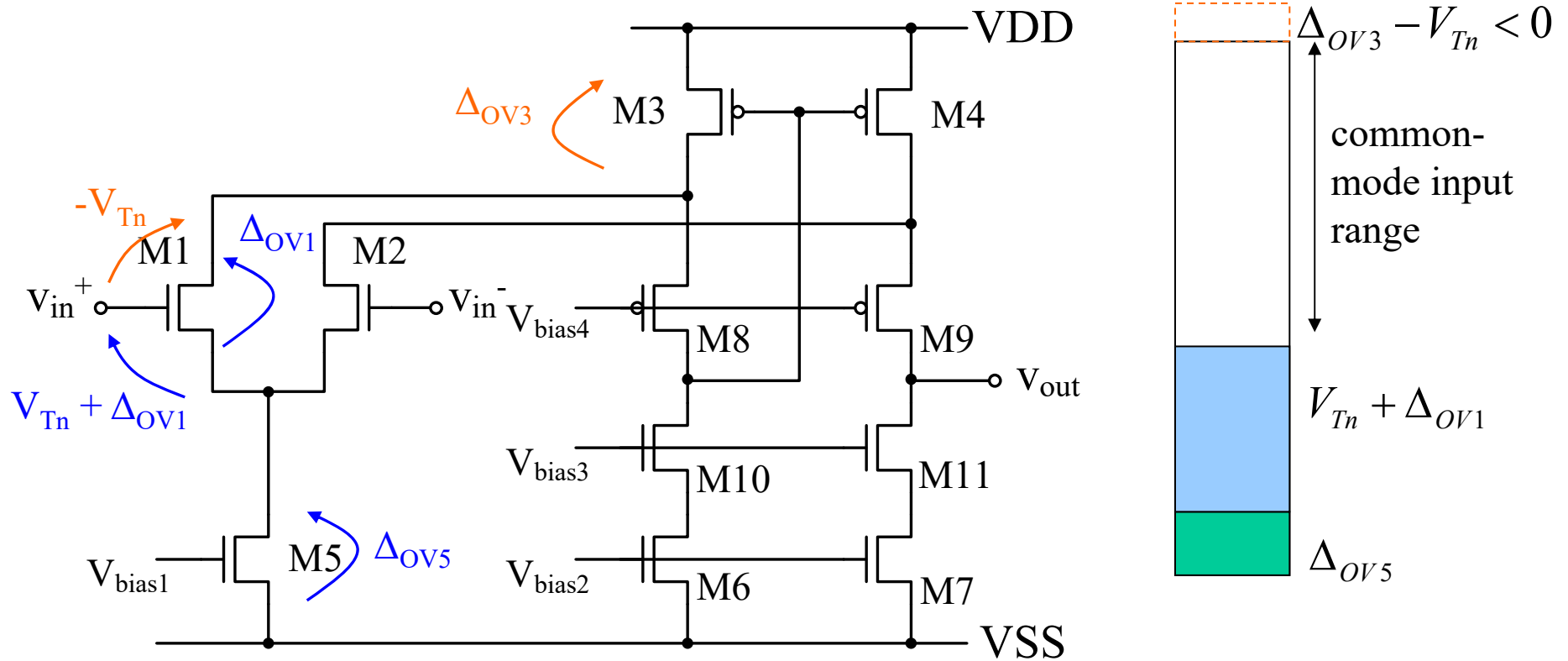
High gain, small input range, and small output swing

Folding technique of the current source load (single-end)

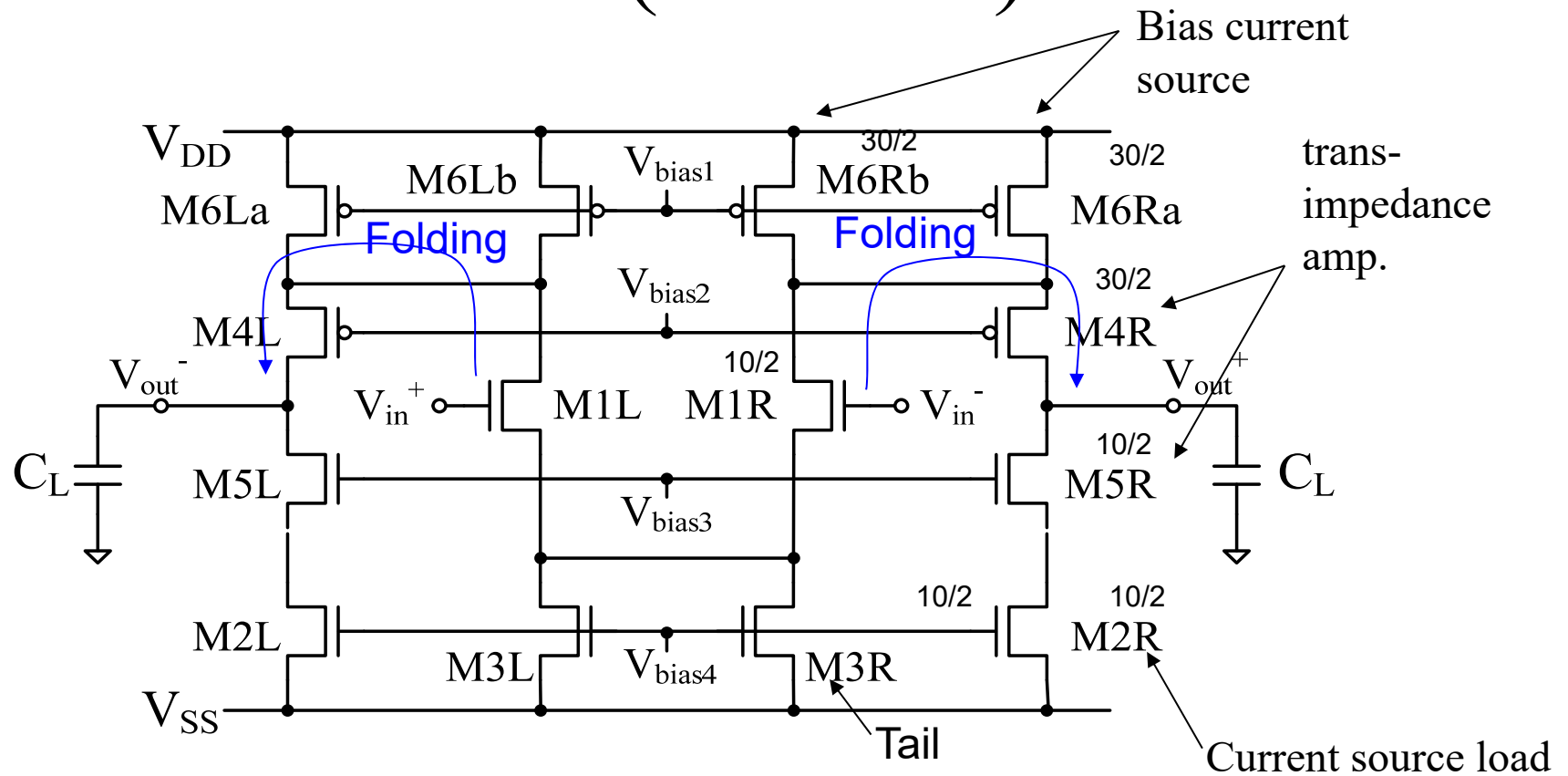
The differential pair and the current source load can be separated to enhance the signal swing and to reduce the bias voltage tolerances.



Common-mode input range of the folded cascode amplifier



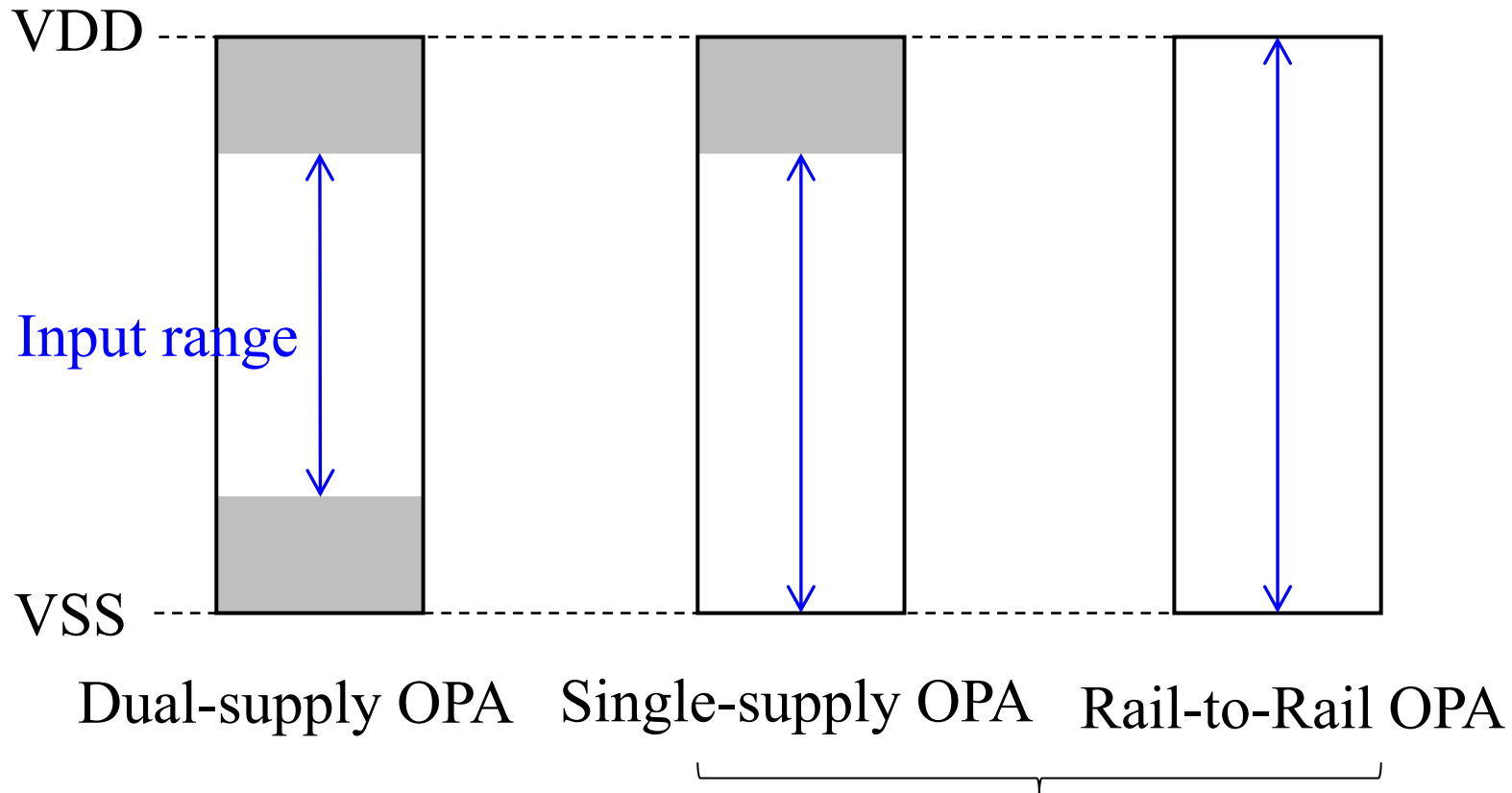
Full-Differential Folded Cascode OPA (or OTA)



(Same as a circuit shown in previous slide)

13.5 Rail-to-Rail OPA

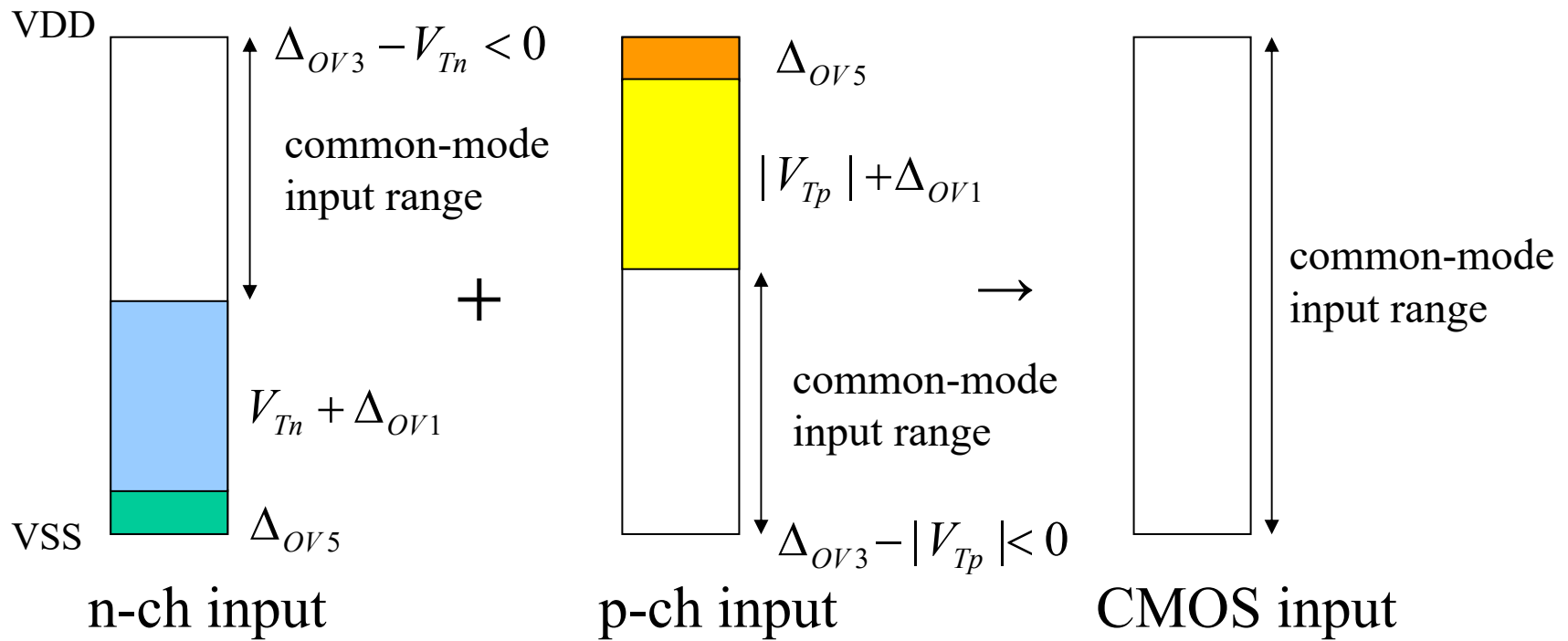
Common mode voltage range of OPA



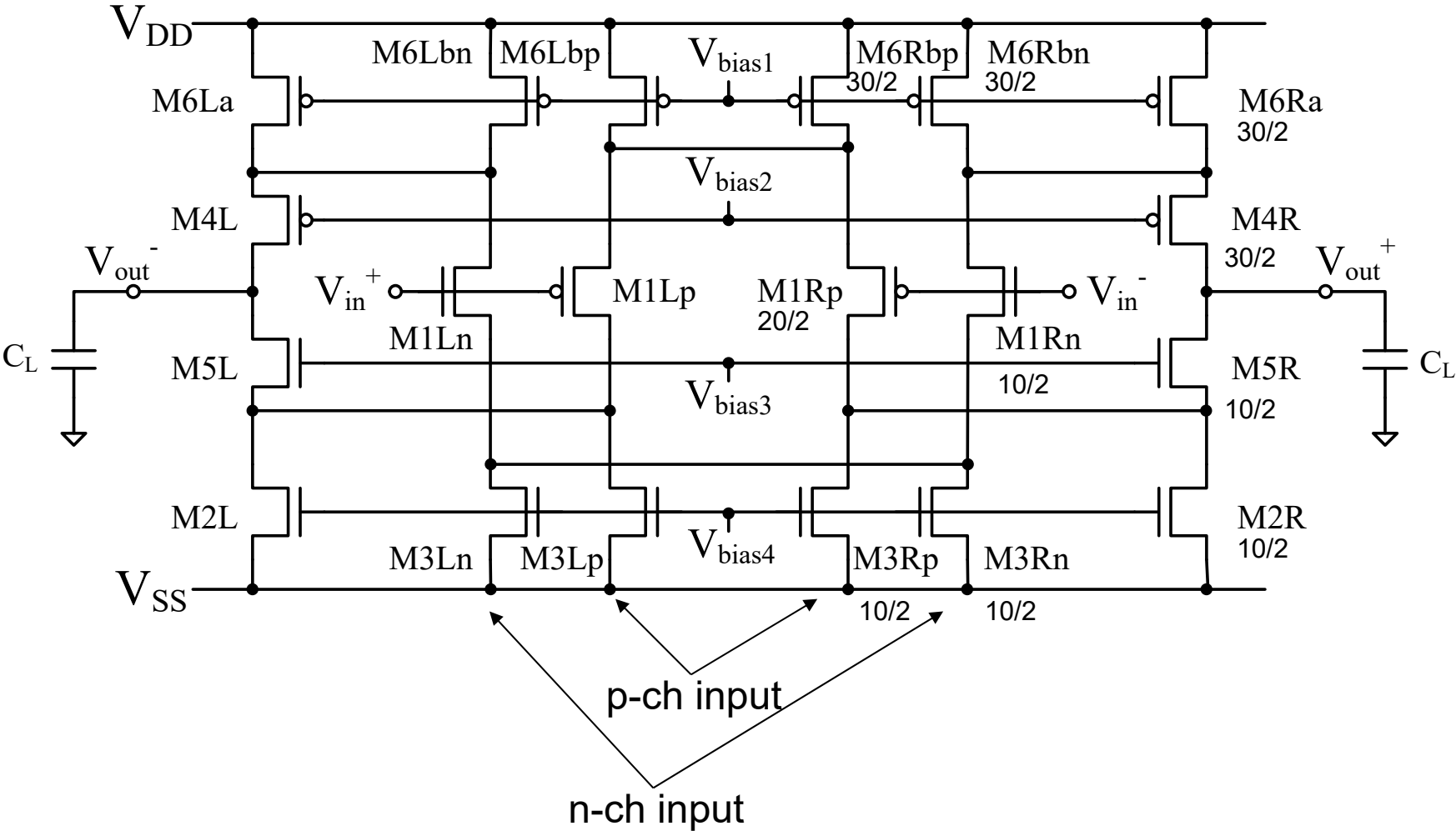
These OPAs operate under the condition that $VSS = GND$. This feature is useful for many sensor applications.

Rail-to-Rail input stage

Rail-to-Rail input OPA can be composed with p-ch differential pair and n-ch differential pair



Rail-to-Rail OPA

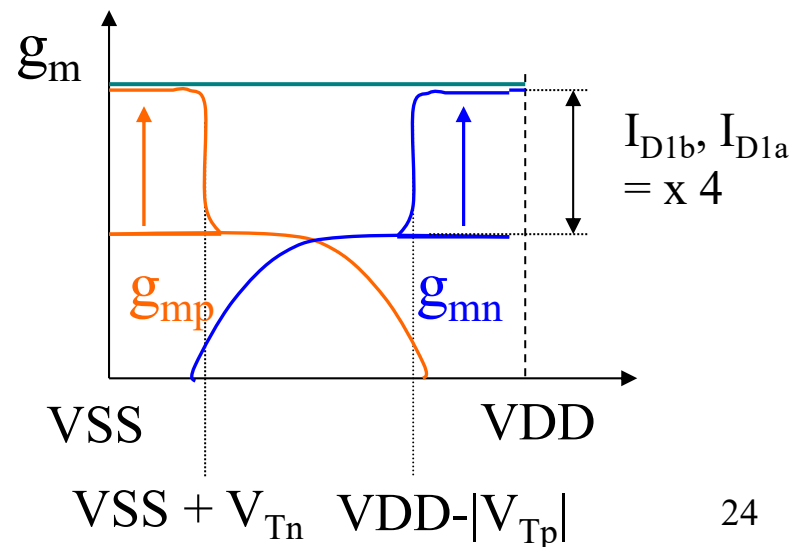
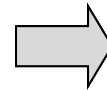
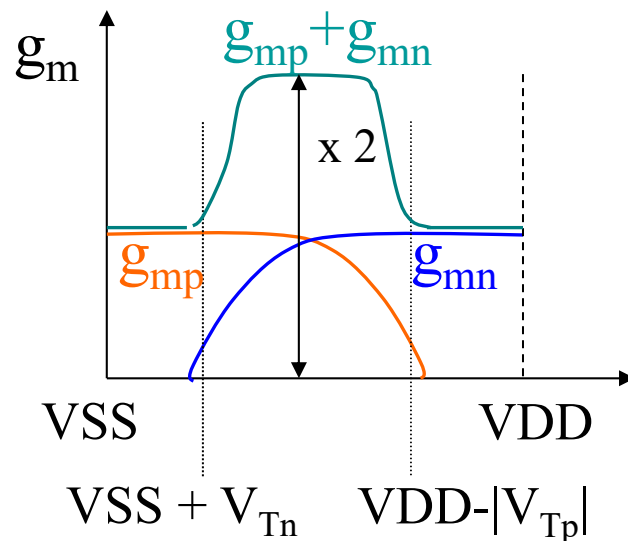


Transconductance uniformity of Rail-to-rail differential amplifier

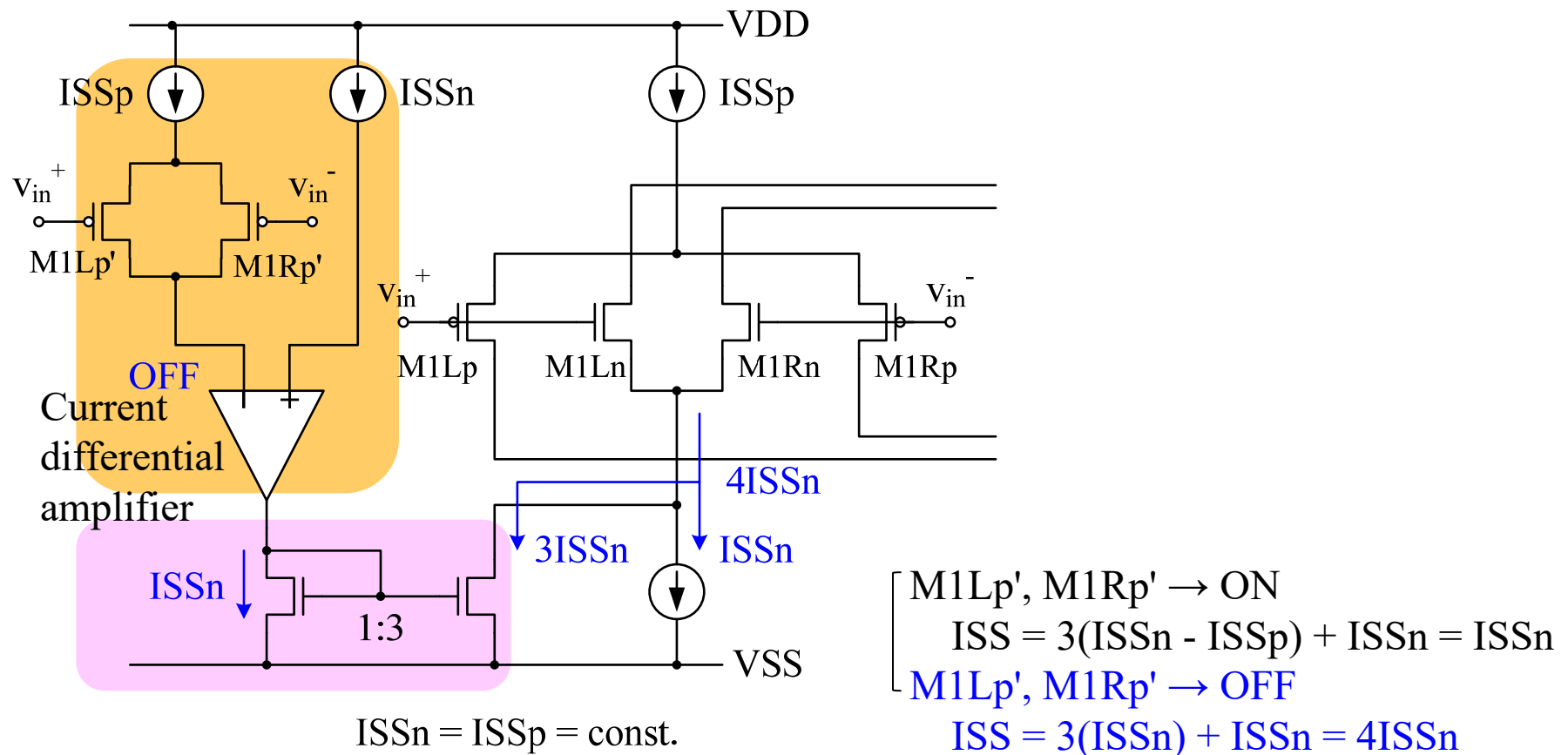
The transconductance of rail-to-rail differential amplifier is not uniform for the input voltage. The nonuniformity raise the nonlinear characteristics. If $\beta_{1n} = \beta_{1p}$,

$$g_m = g_{mn} + g_{mp}$$

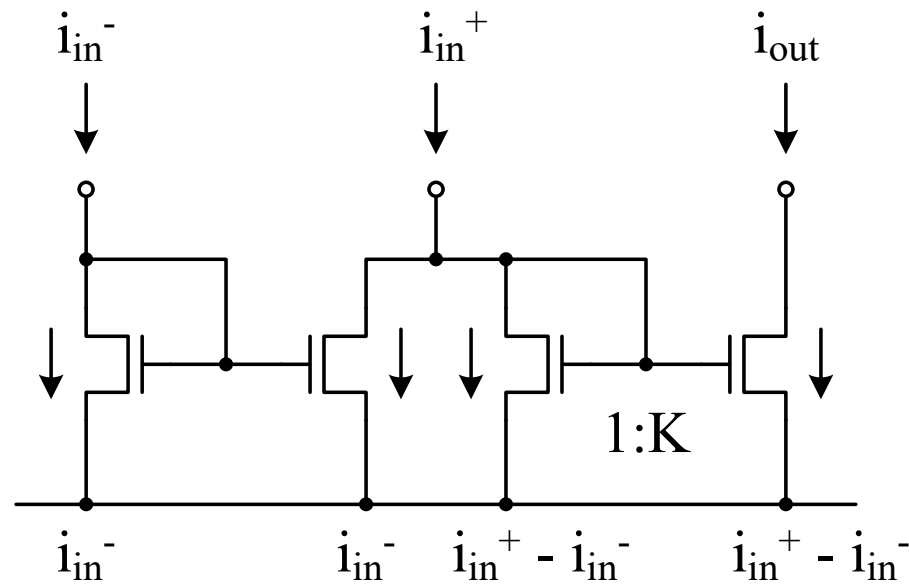
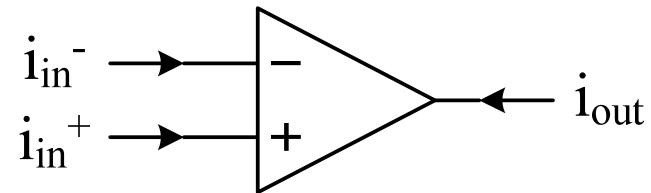
$$= \sqrt{2\beta_{1n}I_{DS1n}} + \sqrt{2\beta_{1p}I_{DS1p}} = \sqrt{2\beta_{1n}} \cdot (\sqrt{I_{DS1n}} + \sqrt{I_{DS1p}})$$



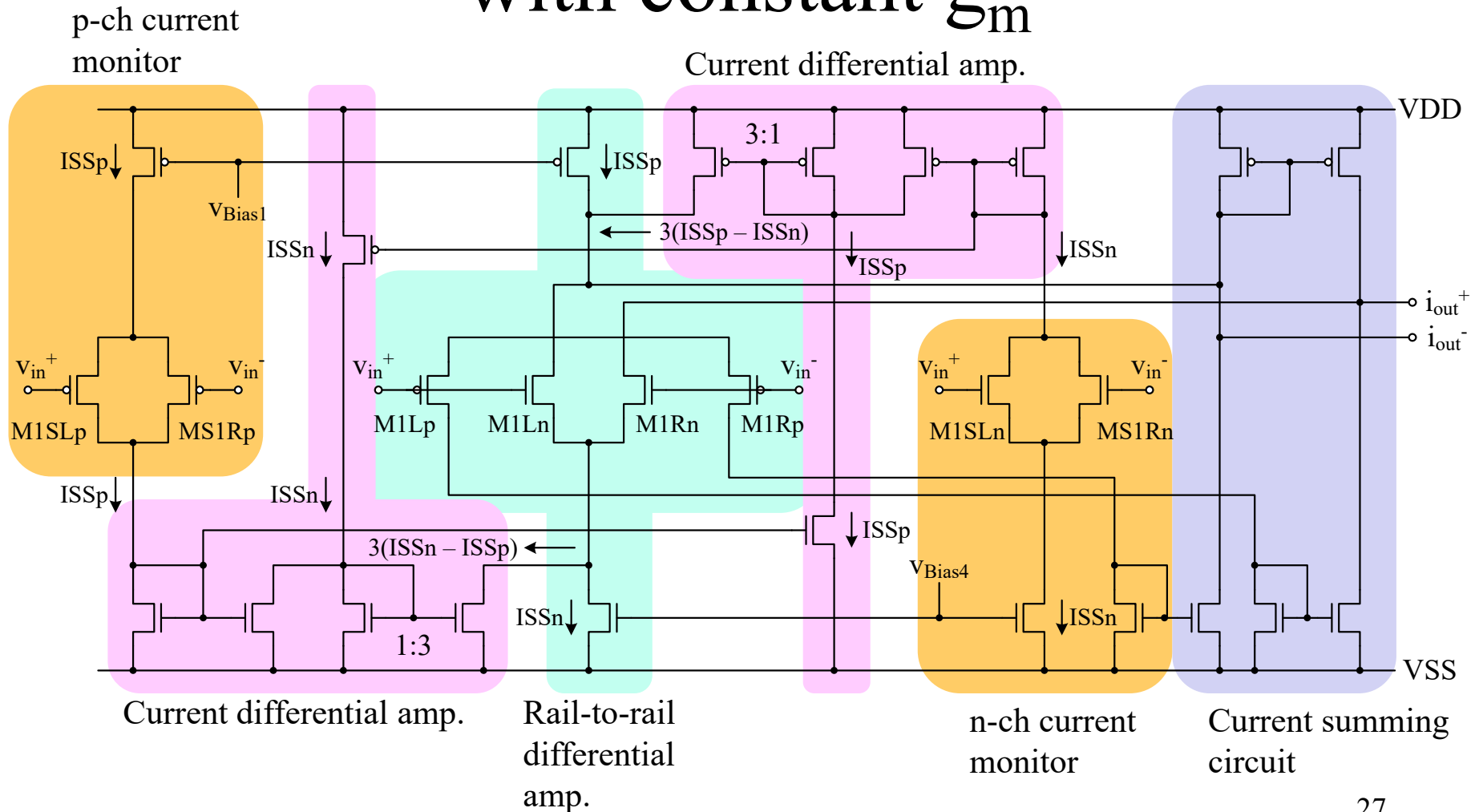
Bias-current control circuit



Current differential amplifier

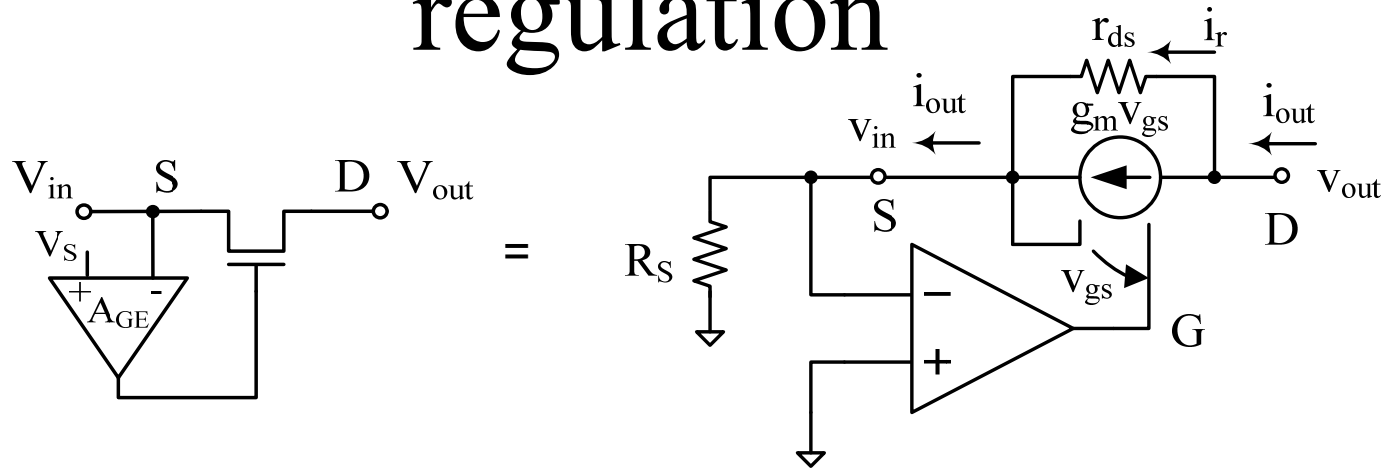


Rail-to-rail differential amplifier with constant g_m



13.6 High gain OPA

Gain enhancement by voltage regulation



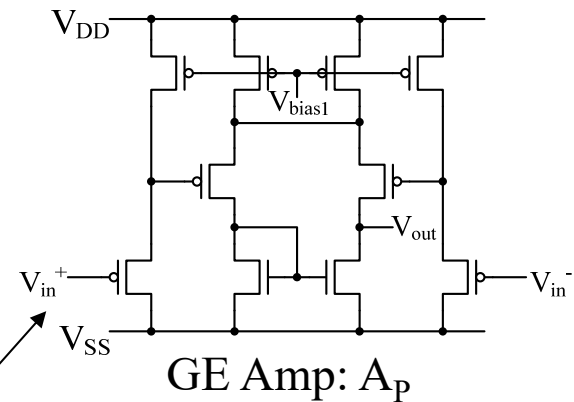
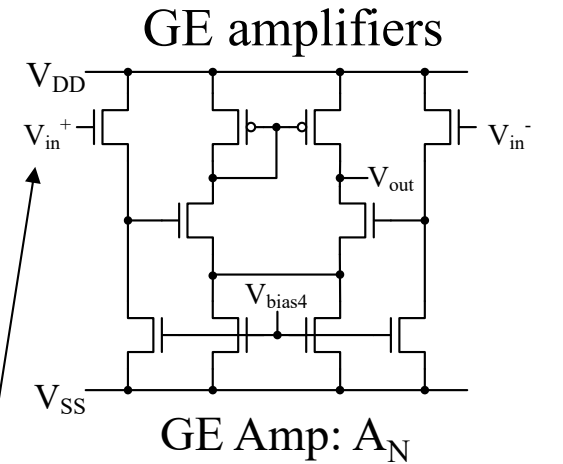
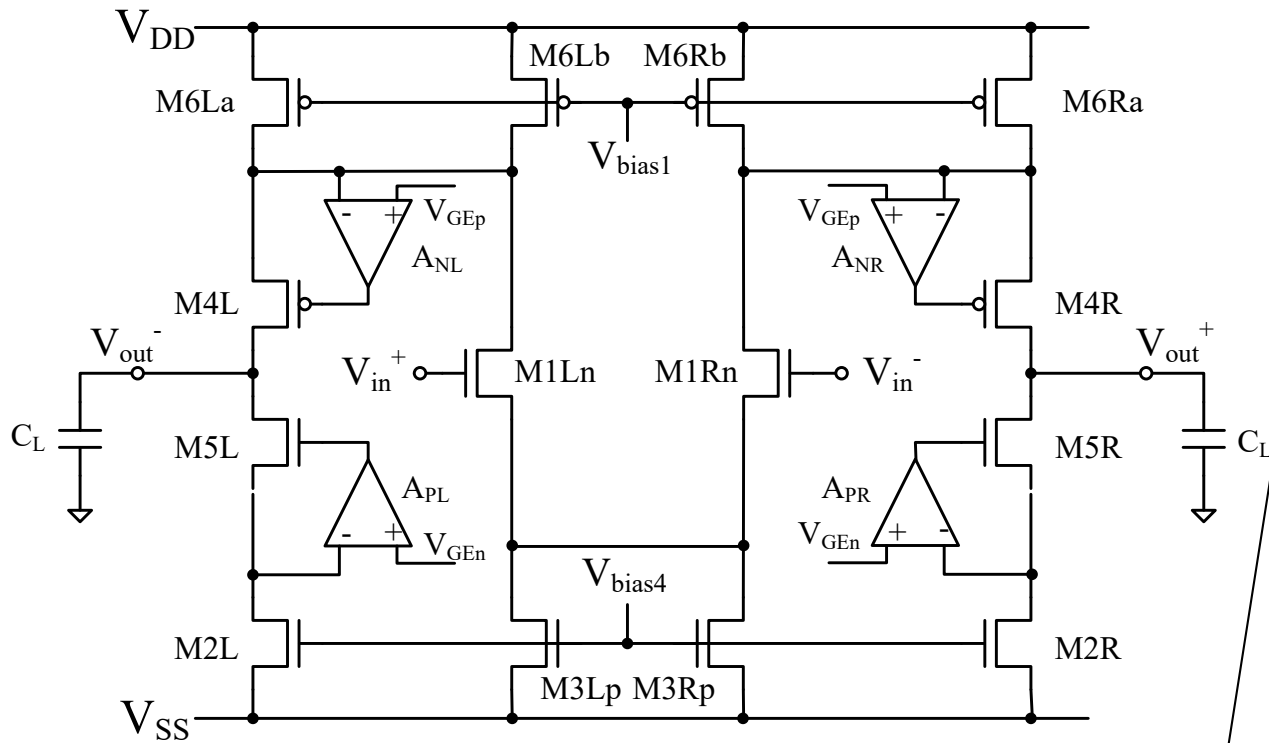
V_{in} is regulated with NFB.

$$\begin{cases} v_{gs} = -A_{GE} \cdot v_{in} - v_{in} \\ v_{in} = R_S i_{out} \\ i_{out} = g_m v_{gs} + i_r \\ v_{out} = r_{ds} i_r + R_S i_{out} \end{cases}$$

$$R_{out} = \frac{v_{out}}{i_{out}} = r_{ds} (1 + g_m (A_{GE} + 1) R_S) + R_S \approx A_V (A_{GE} + 1) R_S$$

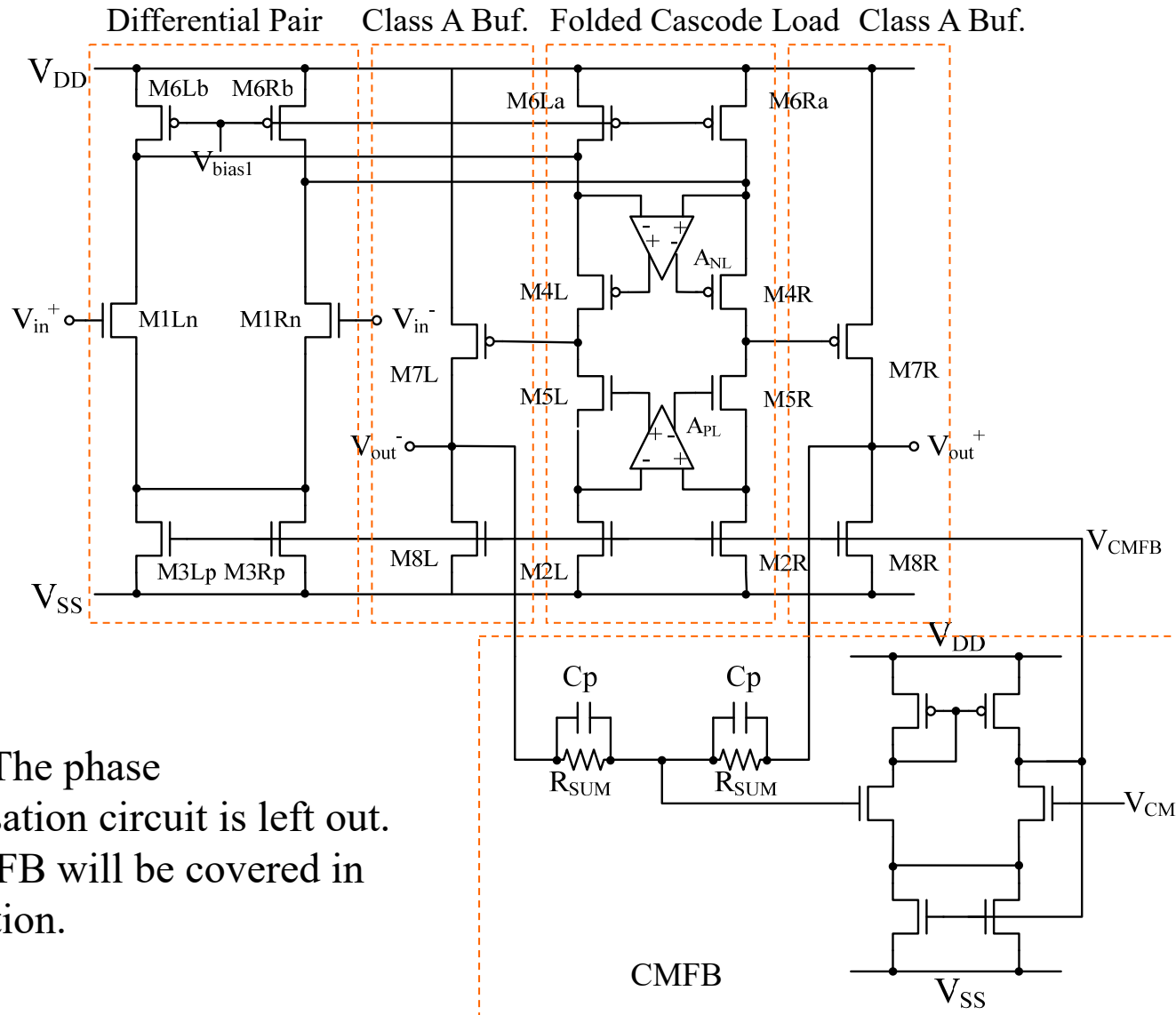
Folded Cascode OPA with gain enhancement (GE) amplifiers

Without GE: $A_d = A_0$, With GE: $A_d = A_0 \cdot (A_p + 1)$



Source follower input (Level shifter)

Design example of GE-FC-OPA

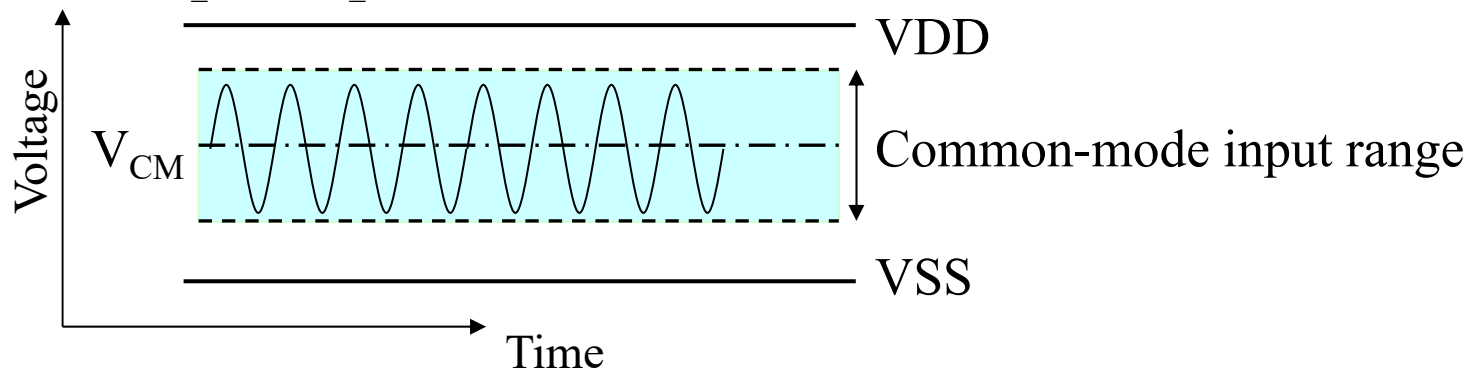


NOTE: The phase compensation circuit is left out. The CMFB will be covered in next section.

13.7 Common mode feedback

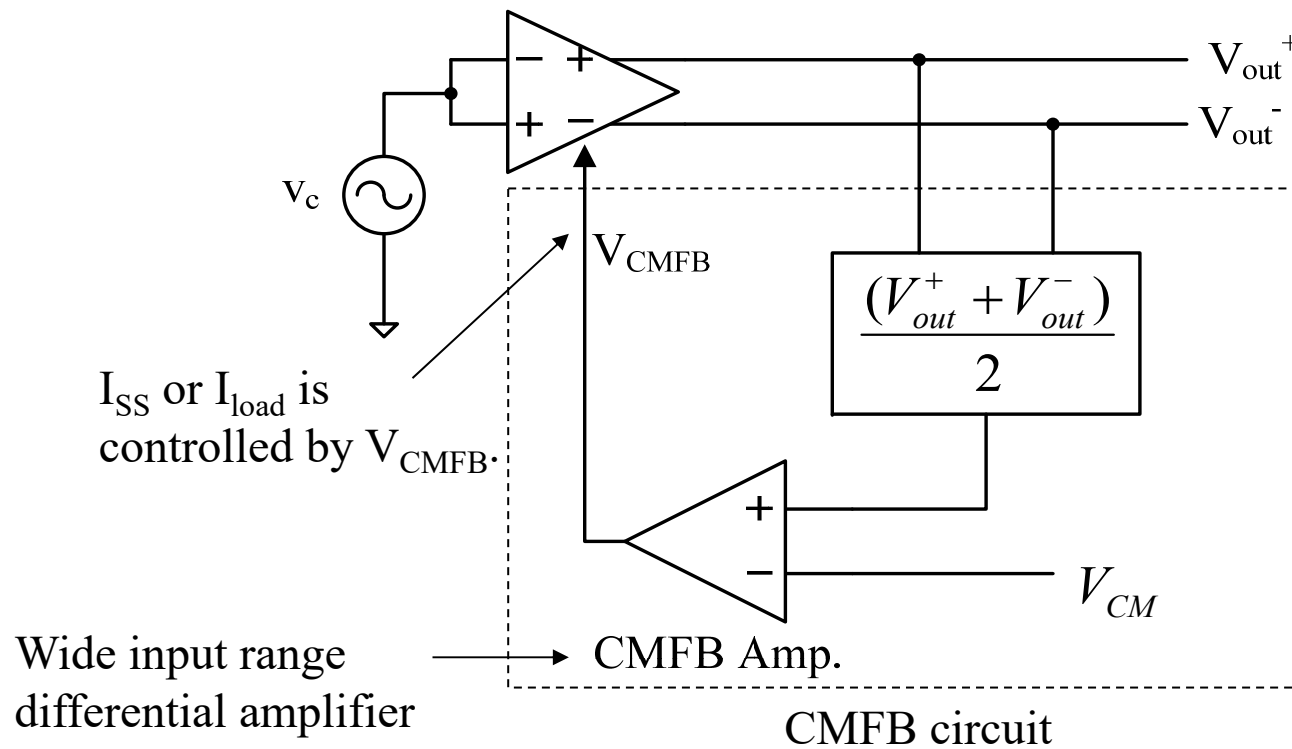
Common Mode Feedback (CMFB)

- Common-mode voltage V_{CM}
 - The common potential of the input and output nodes in the full-differential OPAs cannot be defined in the circuit. Therefore, the full-differential OPAs have to be controlled with the common-mode voltage V_{CM} .
 - The common-mode voltage is applied to the common-mode input.
- I_{SS} or I_{load} should be controlled by the common-mode voltage, because,
 - $I_{load_L} + I_{load_R} > I_{SS} \rightarrow V_{out}^+ = V_{out}^- = VDD$
 - $I_{load_L} + I_{load_R} < I_{SS} \rightarrow V_{out}^+ = V_{out}^- = VSS$

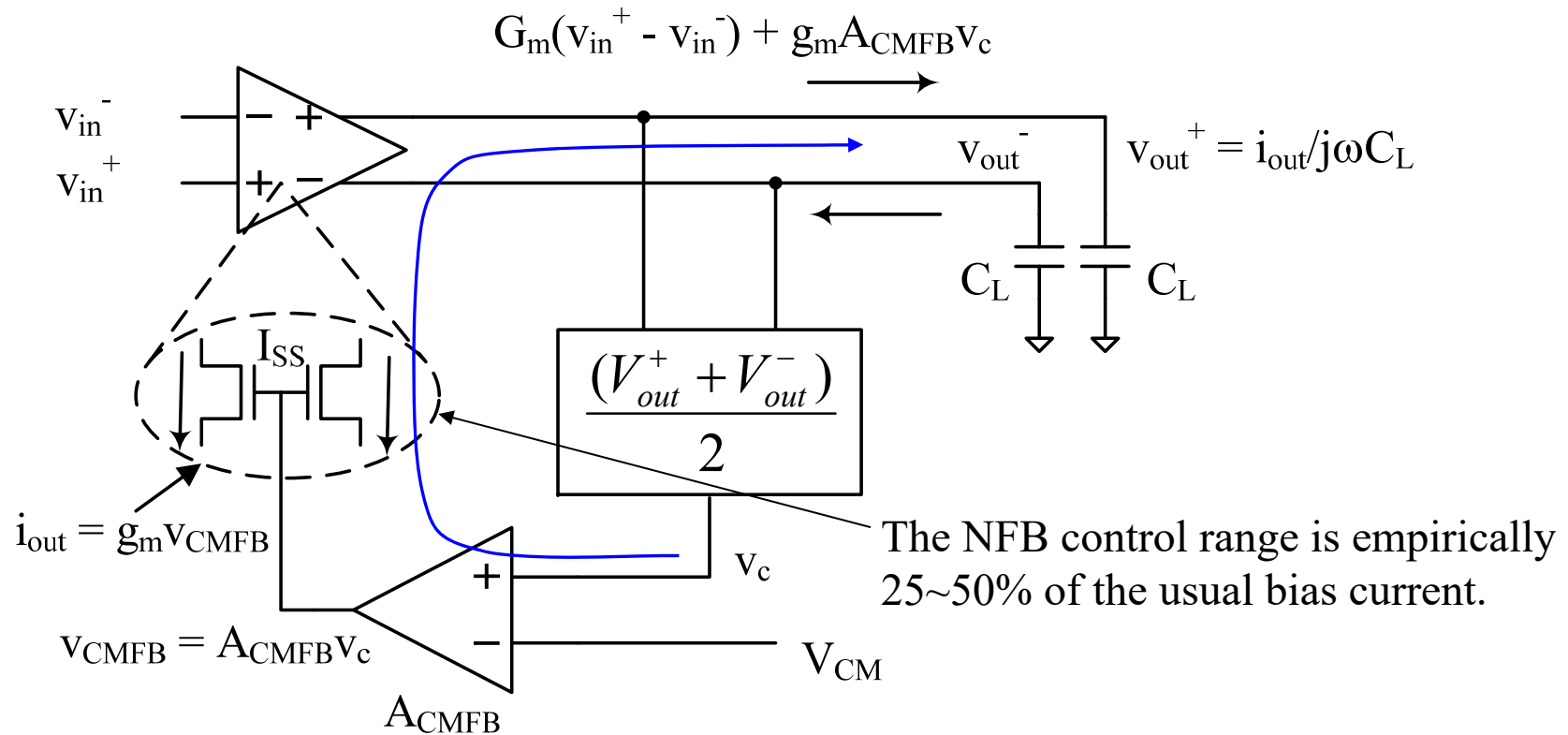


Operation of CMFB

CMFB keeps the bias condition: $I_{D2L} + I_{D2R} = I_{SS}$.



Loop gain of CMFB amplifier

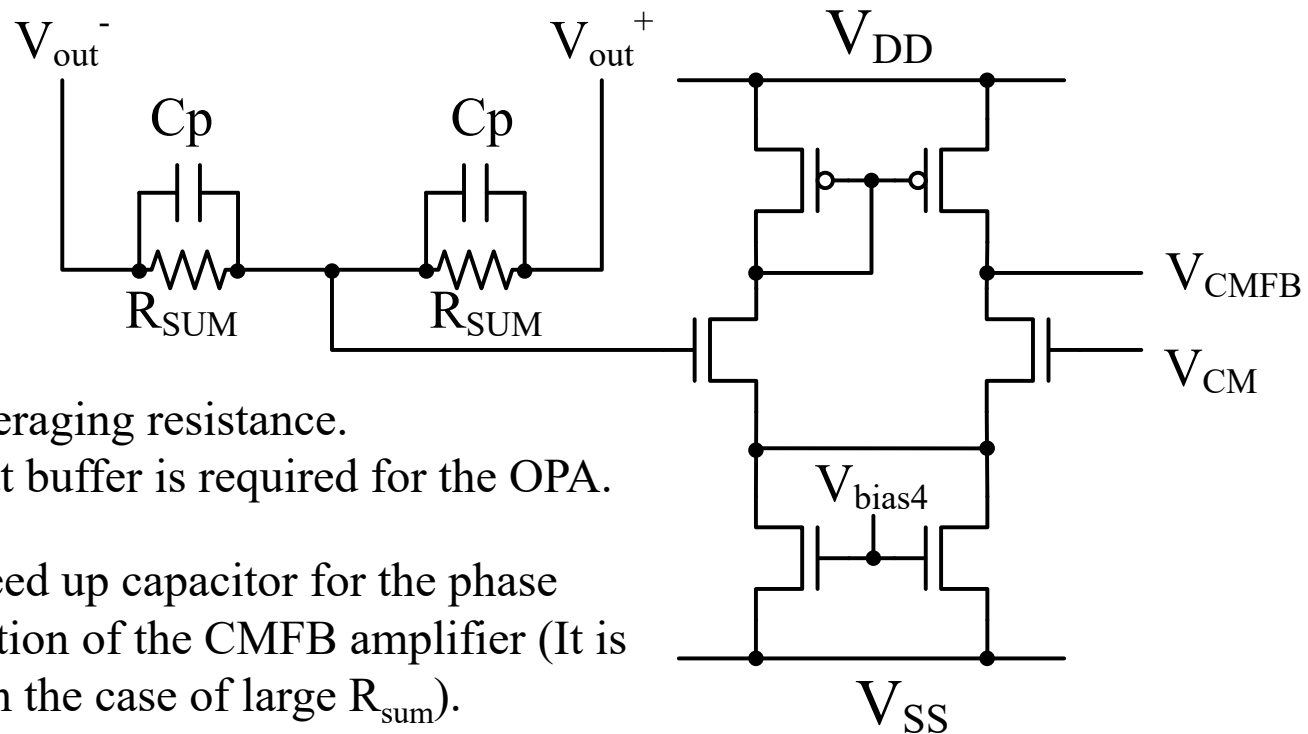


Unity gain frequency of CMFB loop gain

Set the higher A_{CMFB} in the range of $\omega_{u_diff.amp.} > \omega_{uCMFB}$, that is, $A_{CMFB} < 1$.

$$\omega_{uCMFB} = \frac{g_m A_{CMFB}}{C_L}$$

CMFB circuit for continuous-time OPA (1)

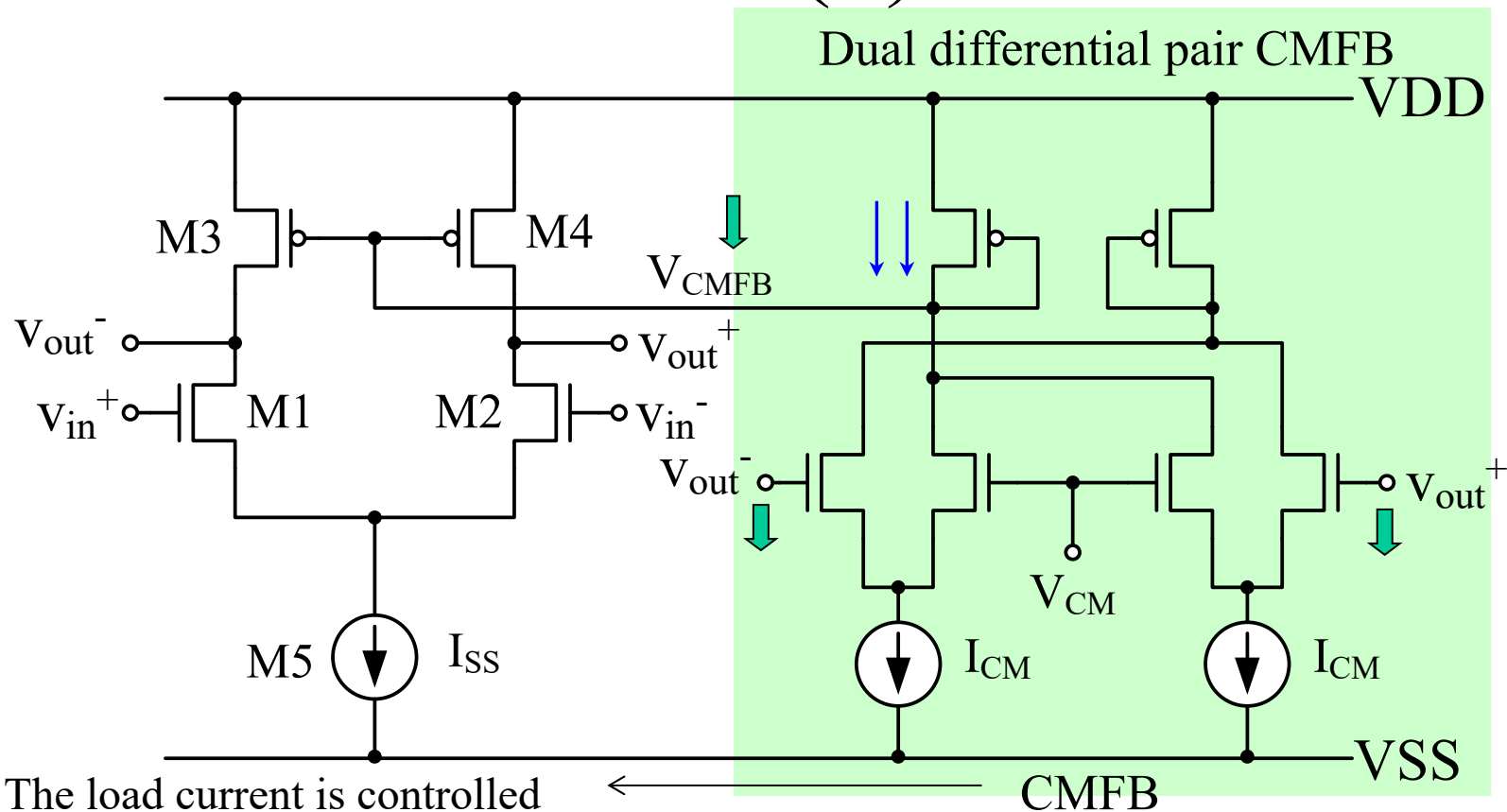


R_{sum} is averaging resistance.
The output buffer is required for the OPA.

C_p is a speed up capacitor for the phase compensation of the CMFB amplifier (It is required in the case of large R_{sum}).

Implementation by the summing amplifier

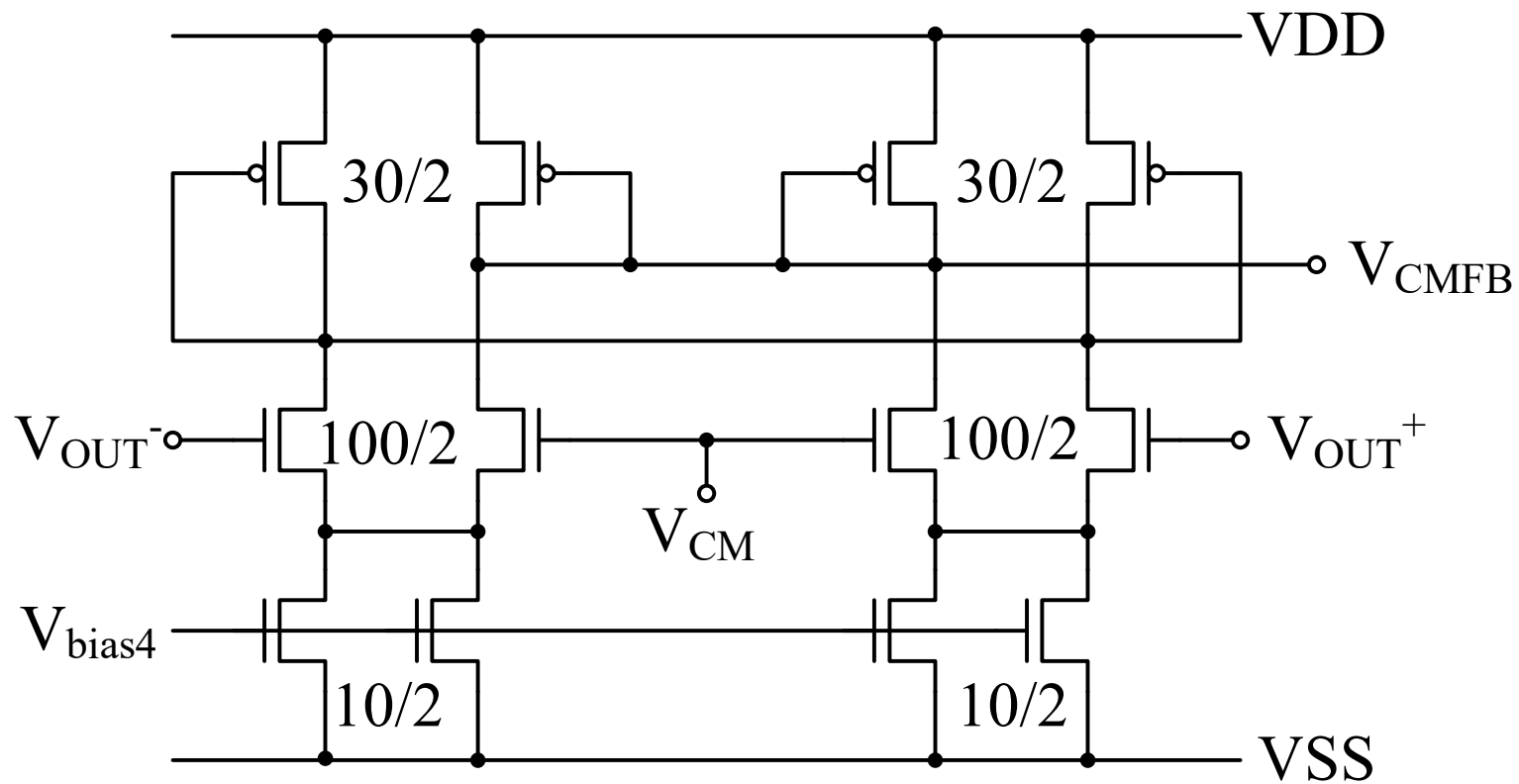
CMFB circuit for continuous-time OPA (2)



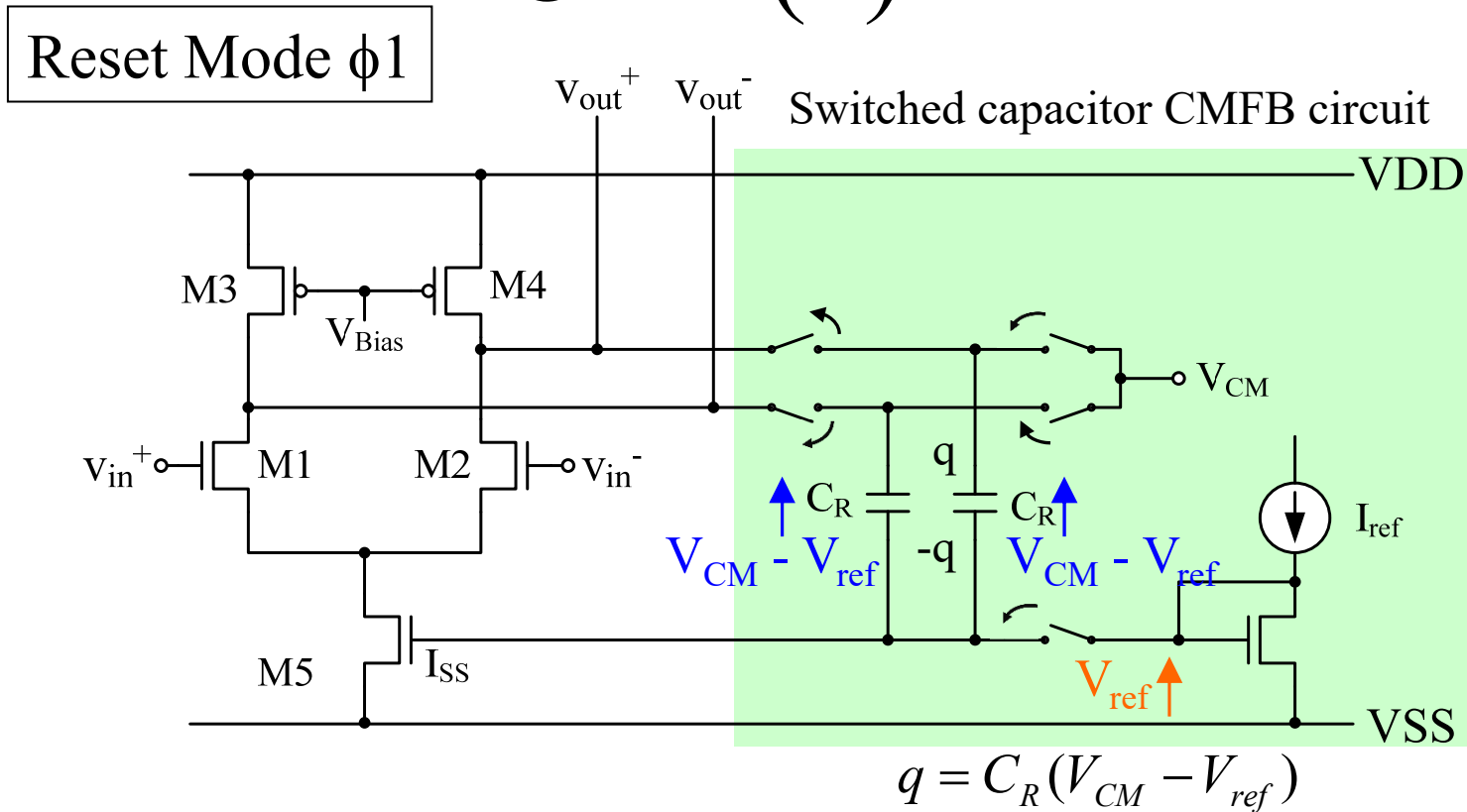
The load current is controlled by the common-mode output referred by V_{CM} .

R.A.Whatley, U.S.Pat. 4, 573, 020, (1986)

Symmetrical implementation of continuous-time CMFB



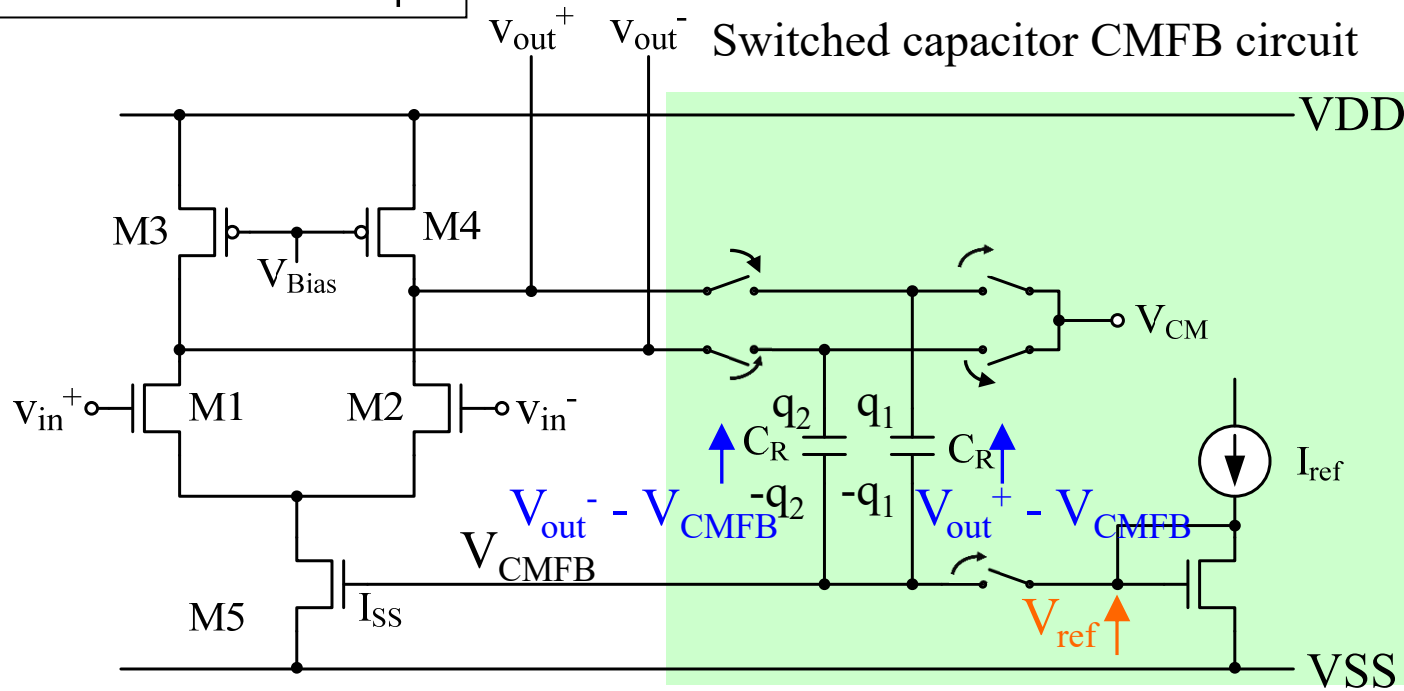
Dynamic CMFB for discrete-time OPA (1)



D. Senderowicz et al., IEEE J. Solid-State Circuits, vol.17, p.1014 (1986)

Dynamic CMFB for discrete-time OPA (2)

Amplification Mode ϕ_2



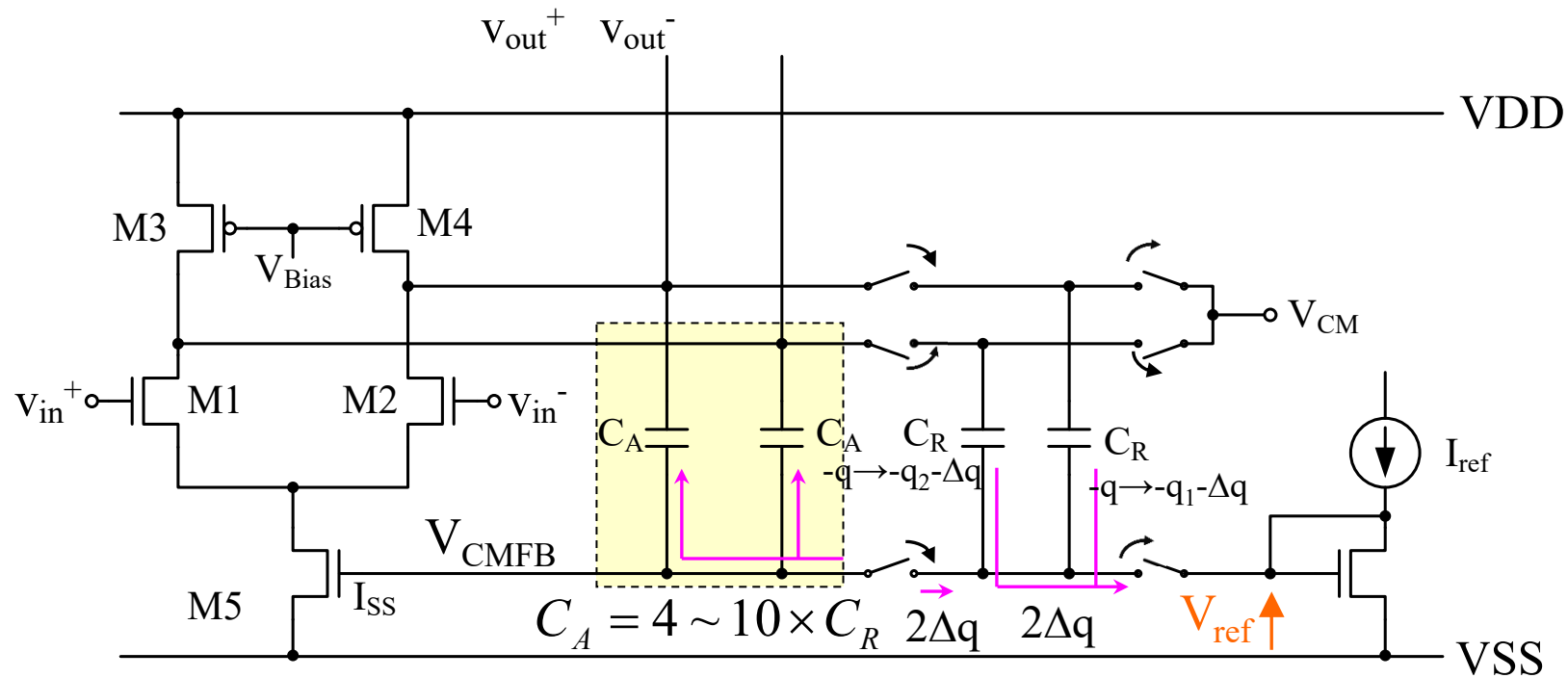
$$\begin{cases} q_1 + q_2 = 2C_R(V_{CM} - V_{ref}) \\ = C_R(V_{out}^+ - V_{CMFB}) + C_R(V_{out}^- - V_{CMFB}) \end{cases}$$

If the common-mode

output = V_{CM} , $I_{SS} = I_{ref}$

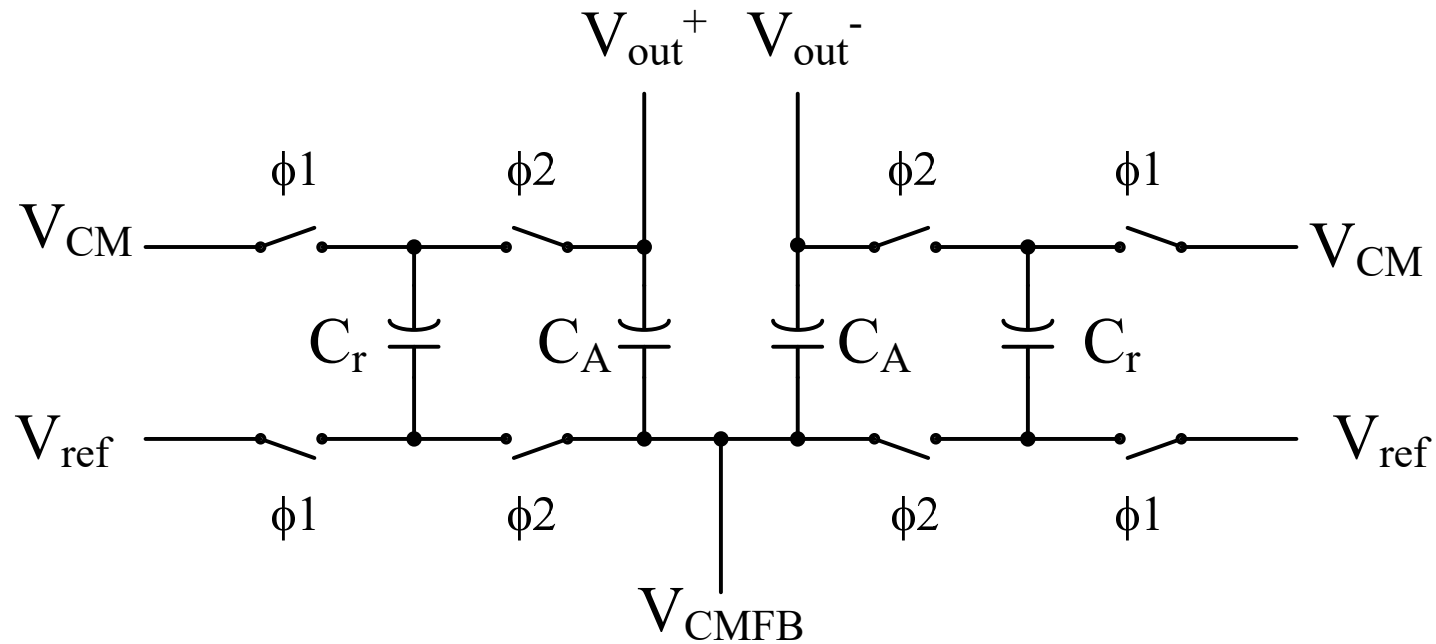
$$V_{CMFB} = \frac{V_{out}^+ + V_{out}^-}{2} - V_{CM} + V_{ref}$$

Cancellation of the parasitic capacitances in the CMOS switch



Cancel of the charge injection error of CMOS switch

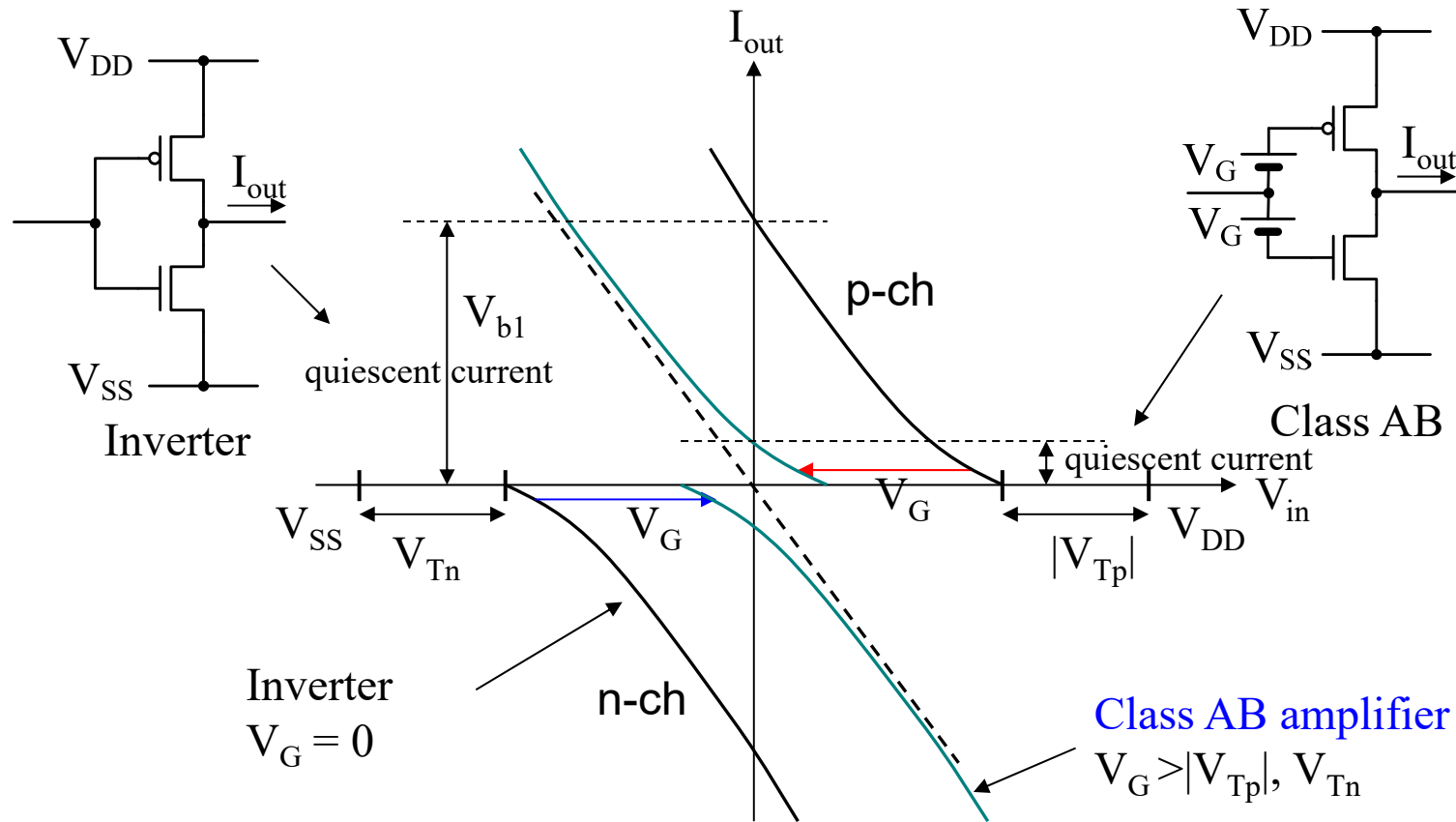
Symmetrical implementation of discrete-time CMFB



Symmetric schematic (intended for layout design)

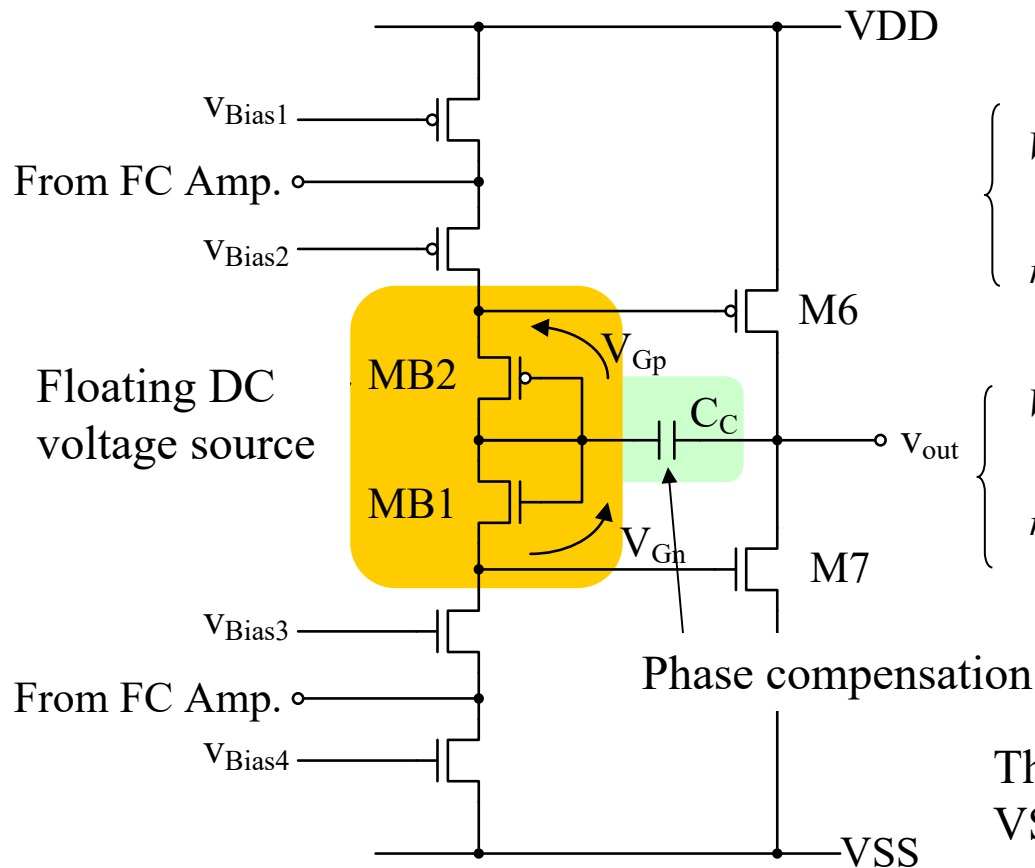
13.8 Output buffer for OPA

Class AB output buffer



NOTE: Class A amplifier (current source load) and Class AB amplifier is often used for the output buffer of OPA.

Floating DC voltage source

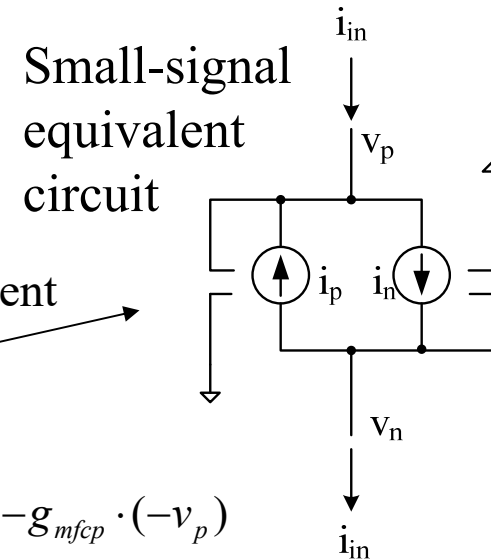
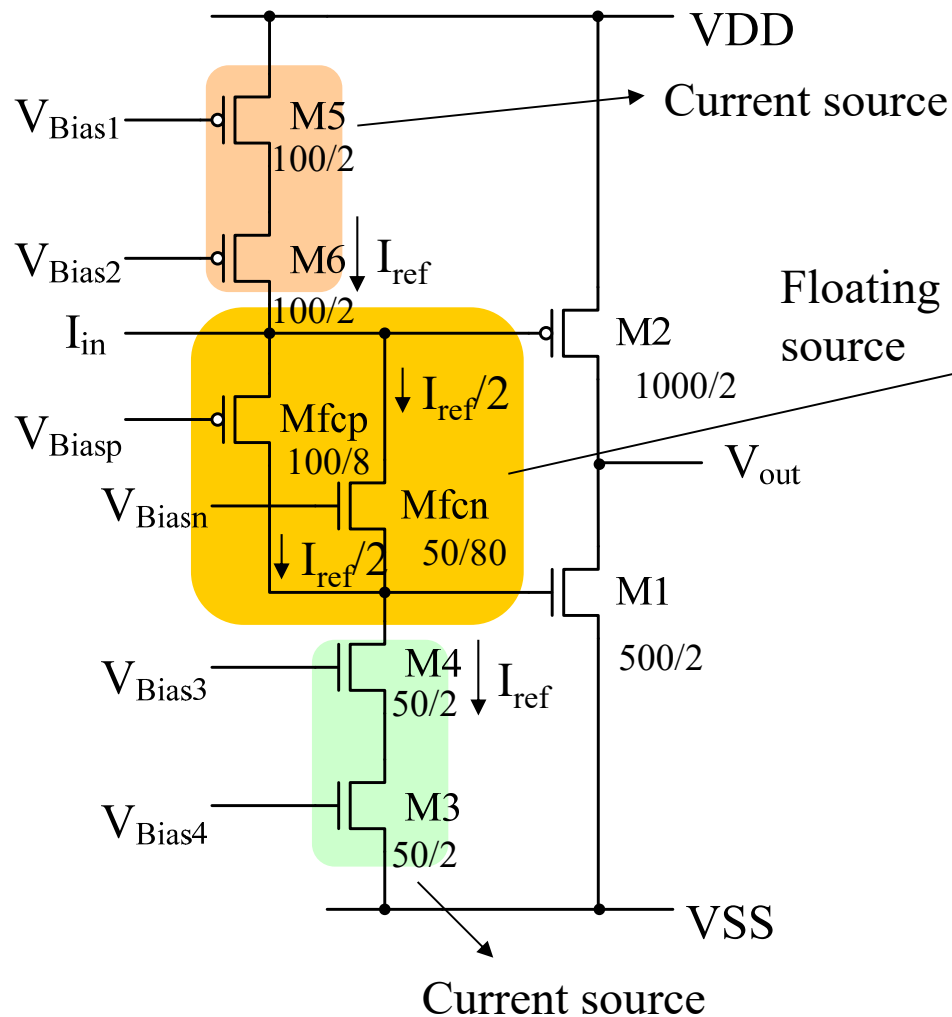


$$\left\{ \begin{array}{l} V_{Gp} = |V_{Tp}| + \sqrt{\frac{2I_{DS_MB2}}{\beta_p}} \quad \text{Floating DC voltage} \\ r_{ds_MB2} \cong \frac{1}{g_{m_MB2}} = 1 / \sqrt{2\beta_p I_{DS}} \geq \frac{1}{g_{m6}} \quad \text{Zero cancel} \end{array} \right.$$

$$\left\{ \begin{array}{l} V_{Gn} = V_{Tn} + \sqrt{\frac{2I_{DS_MB1}}{\beta_n}} \quad \text{Floating DC voltage} \\ r_{ds_MB1} \cong \frac{1}{g_{m_MB1}} = 1 / \sqrt{2\beta_n I_{DS}} \geq \frac{1}{g_{m7}} \quad \text{Zero cancel} \end{array} \right.$$

The output voltage swing is limited within $VSS + V_{Tn} + 3\Delta_{OV}$ and $VDD - |V_{Tp}| - 3\Delta_{OV}$.

Common gate level shift



$$i_p = -g_{mfc} \cdot (-v_p)$$

$$i_n = -g_{mfc} \cdot v_n$$

$$i_{in} = i_n - i_p = -g_{mfc} \cdot v_n - g_{mfc} \cdot v_p$$

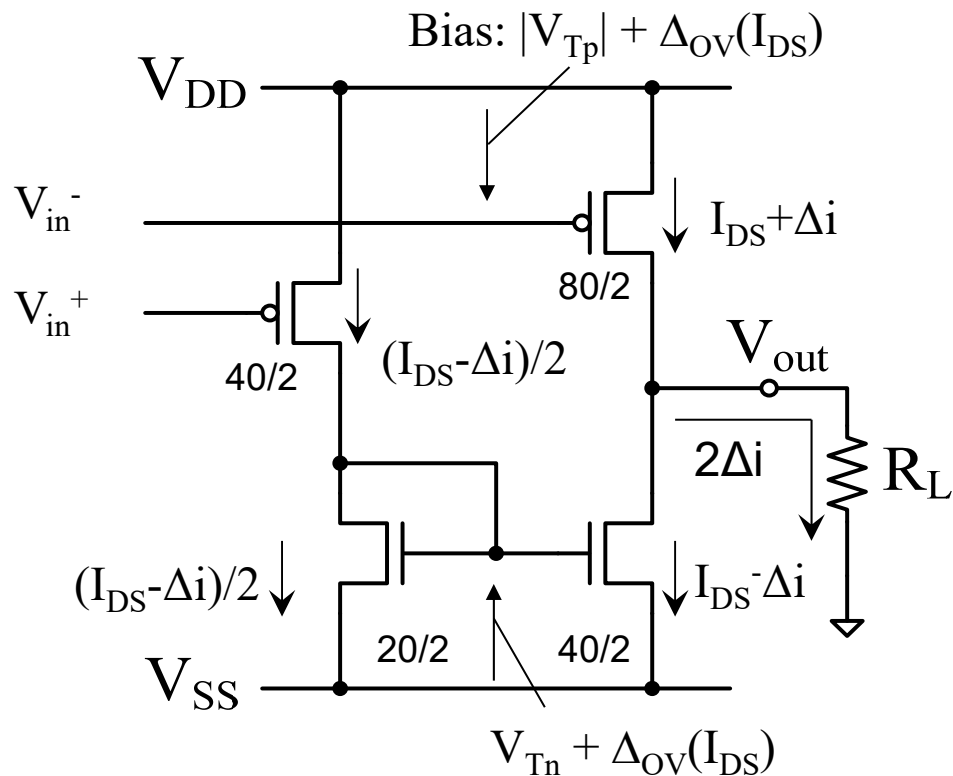
$$\text{If } g_{mfc} = g_{mfc} \equiv g_{mfc}$$

$$i_{in} = 2g_{mfc} \left(\frac{v_p + v_n}{2} \right)$$

An average potential of v_p and v_n is proportional to i_{in} .

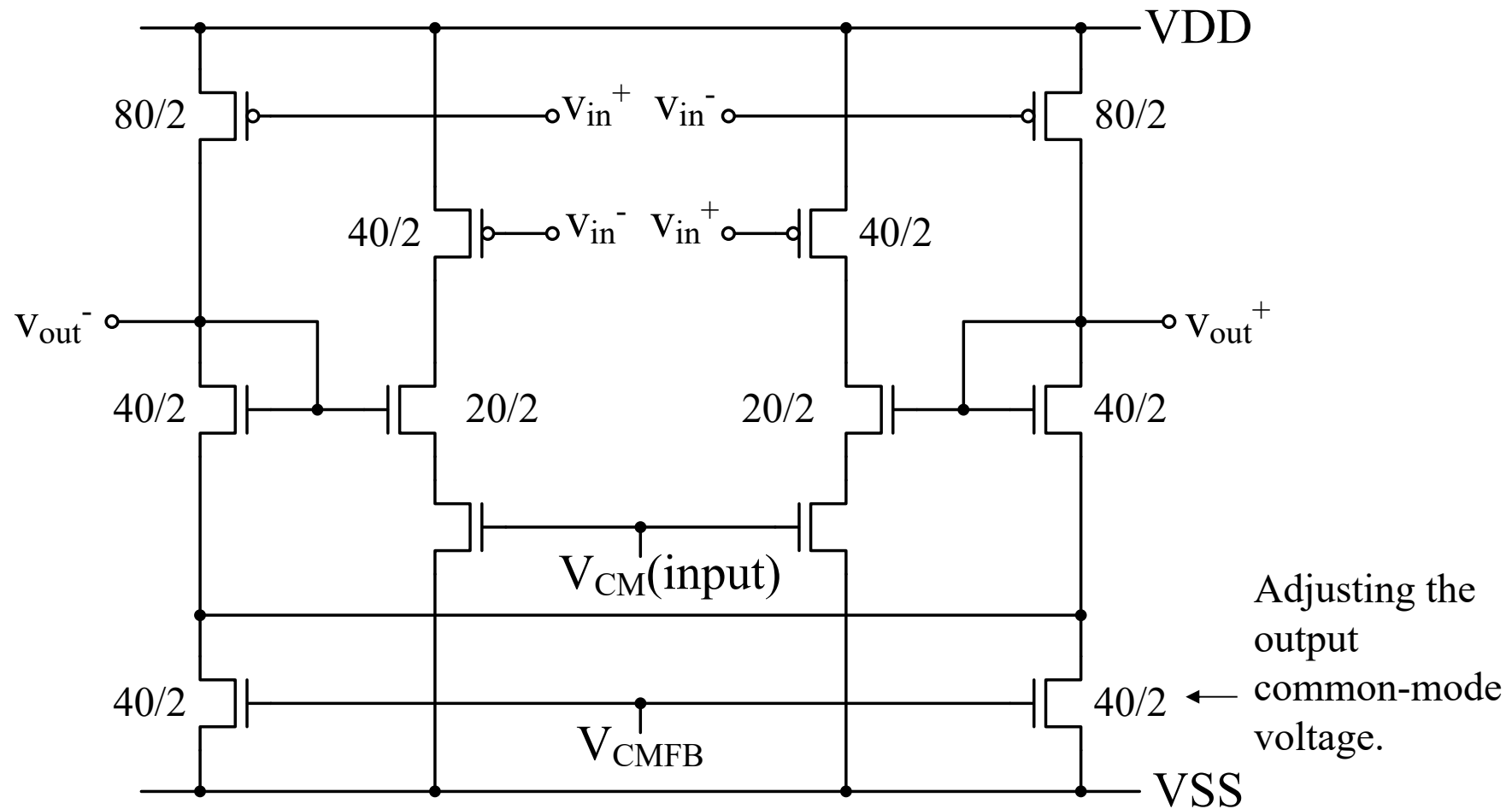
Class AB differential buffer for OPA

I_{DS} : Idling Current, Δi : Current Signal



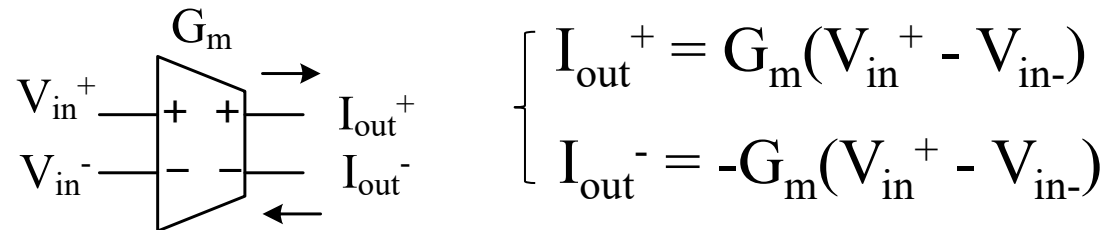
(Don't use this circuit. This circuit is not available for CMFB.)

Practical class AB differential buffer



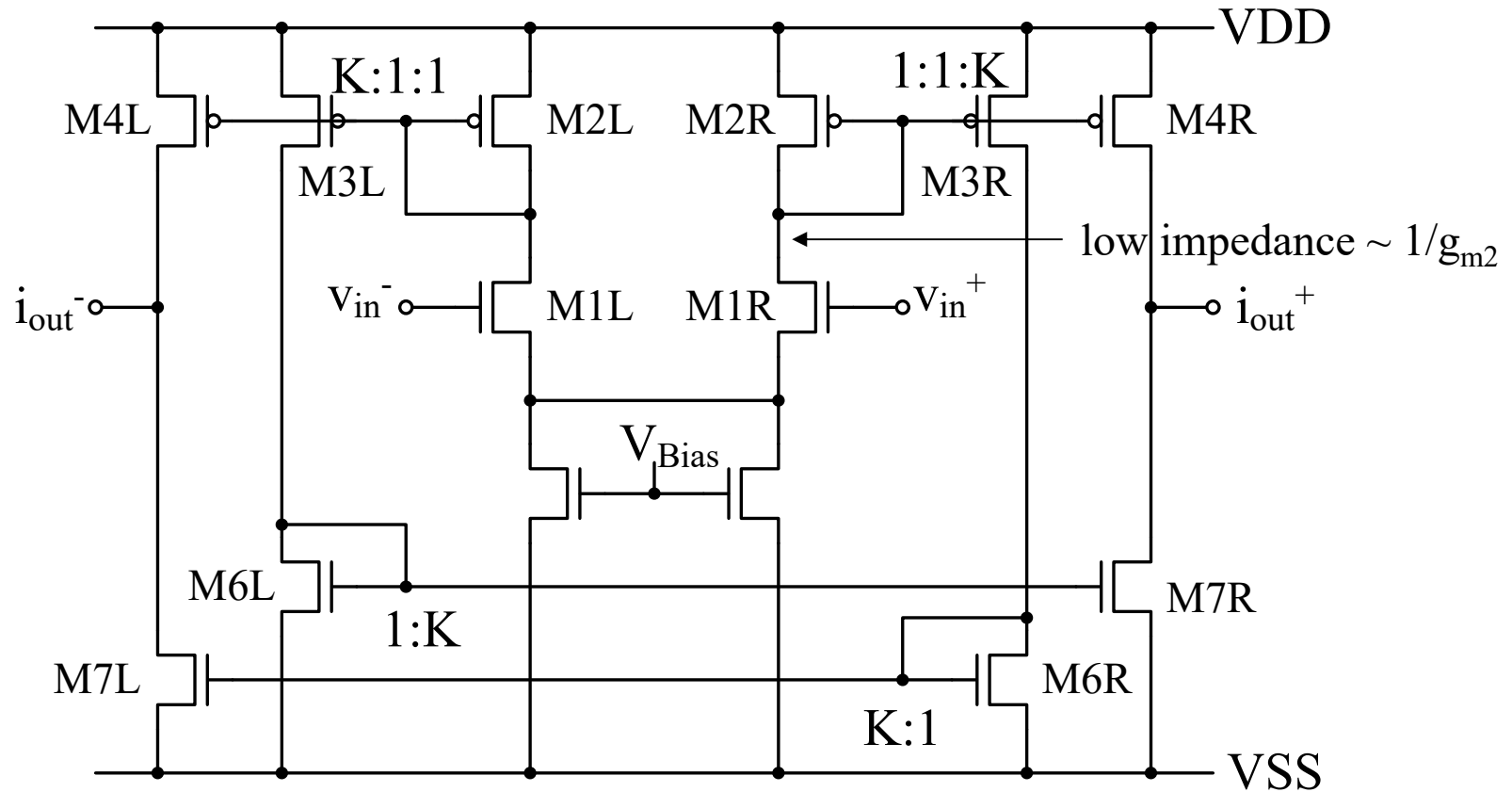
13.9 Operational transconductance amplifier (OTA)

Functions of OTA



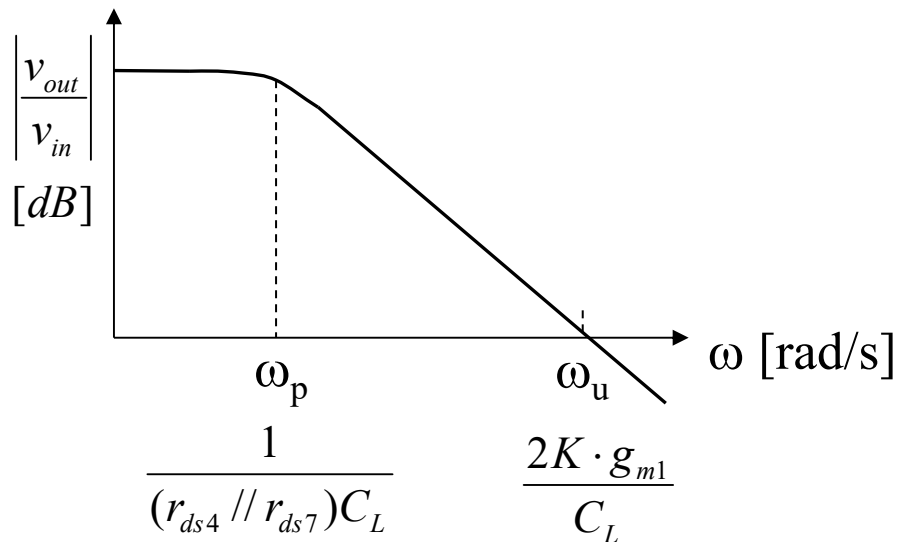
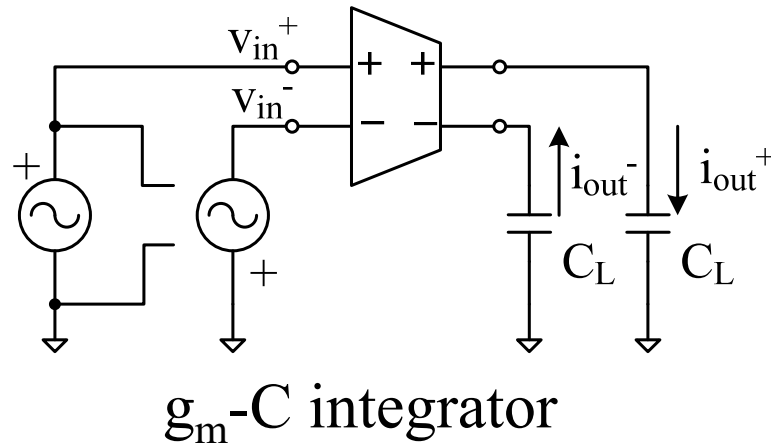
- Differential voltage input and differential current output
- All node are low impedance except the input and output nodes.
- Differences with OPA
 - High output resistance
 - OTA cannot drive the resistive load.
 - Unity gain frequency decreases with increasing C_L .
 - This characteristic is used in the g_m -C filters.
 - Phase margin increases with increasing C_L .
 - OPA become unstable with a large C_L .

Circuit configuration of OTA



$$i_{out}^+ = K \cdot g_{m1} (v_{in}^+ - v_{in}^-) = G_m (v_{in}^+ - v_{in}^-)$$

Characteristics of gm-C filter



$$v_{out}^+ = \frac{1}{j\omega C_L} i_{out}^+ = \frac{K \cdot g_{m1}}{j\omega C_L} (v_{in}^+ - v_{in}^-)$$

$$A_d = \frac{v_{out}^+ - v_{out}^-}{v_{in}^+ - v_{in}^-} = \frac{2K \cdot g_{m1}}{j\omega C_L}$$

$$\omega_u = \frac{2K \cdot g_{m1}}{C_L}$$

$$\omega_p = \frac{1}{(r_{ds4} // r_{ds7})C_L}$$

$$SR = \frac{K \cdot ISS}{C_L}$$

(The maximum current of M4 is $K \cdot ISS$.)

Cascode OTA

