13. Full-differential operational amplifier

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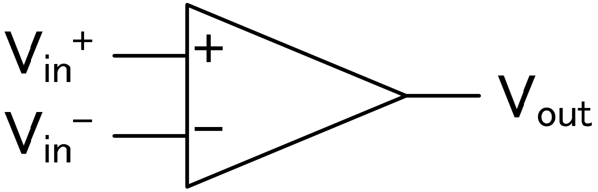
13.1 The foundations of Full-differential OPA

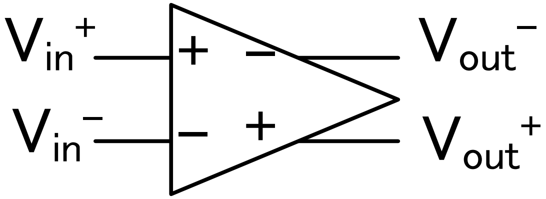
Function of a full-differential OPA



Symbol of Single-end OPA

Function

$$\begin{cases} V_{out} = A_d(V_{in}^+ - V_{in}^-) \\ \text{A}_\text{d} = \text{Differential Gain} \end{cases}$$



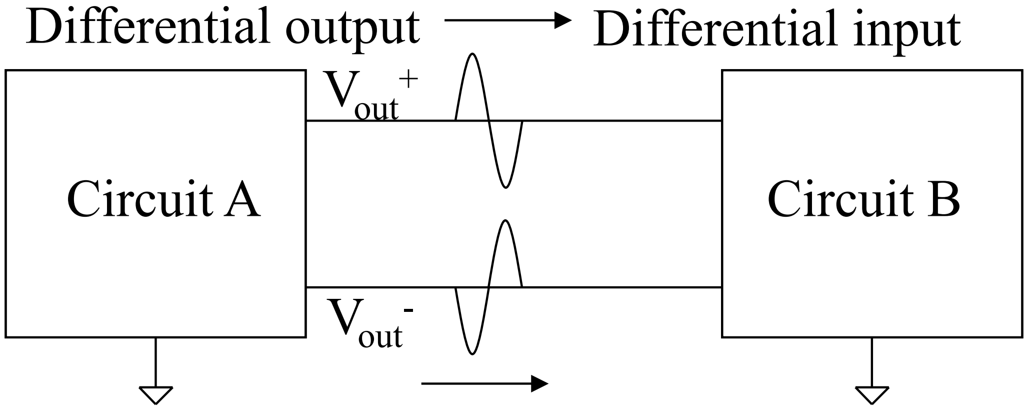
Symbol of Full-differential

$$\begin{cases} V_{out}^+ = \dfrac{A_d}{2}(V_{in}^+ - V_{in}^-) \\ V_{out}^- = -\dfrac{A_d}{2}(V_{in}^+ - V_{in}^-) \\ V_{out} = V_{out}^+ - V_{out}^- \end{cases}$$

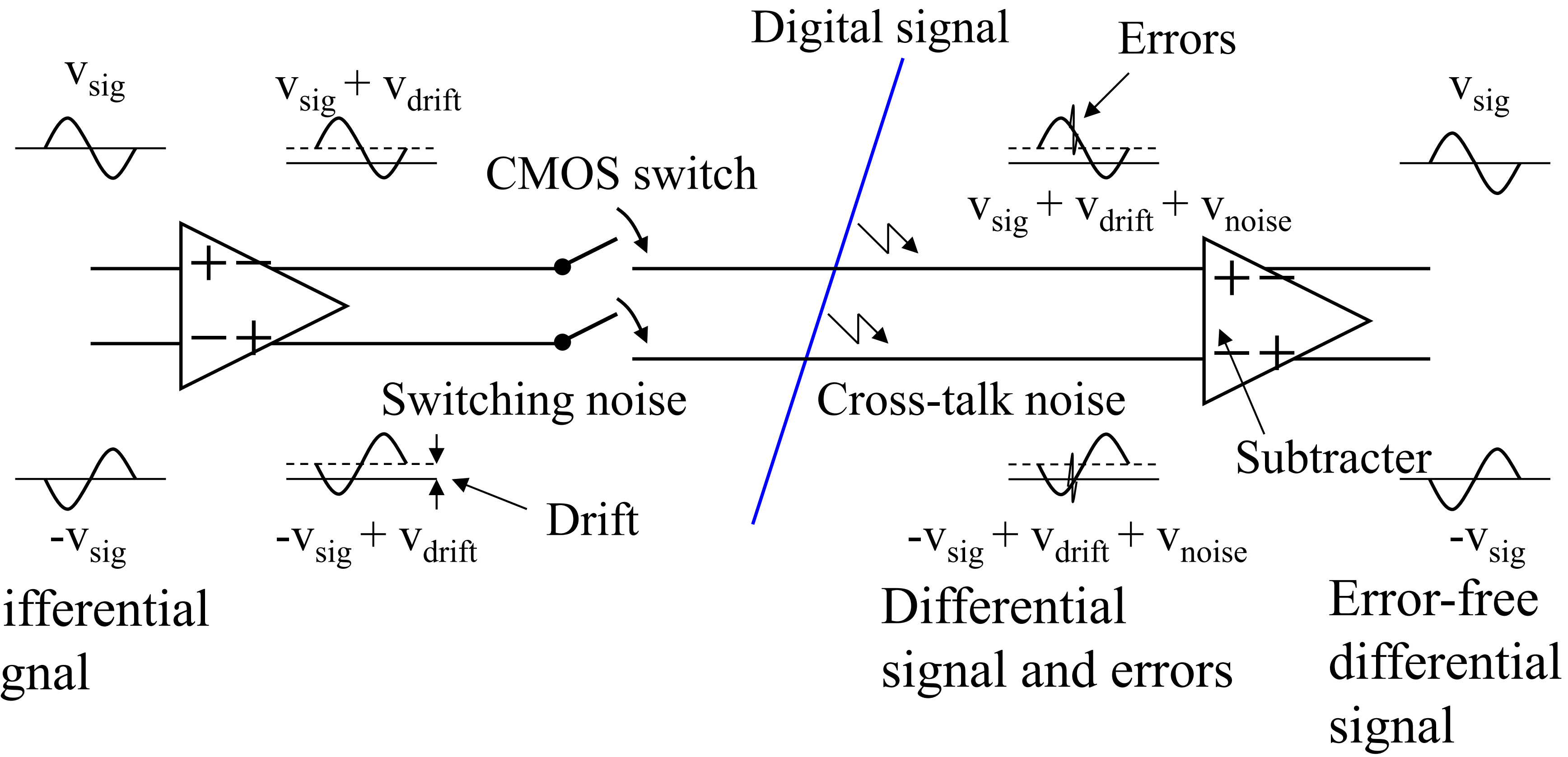
A_d = Differential Gain

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



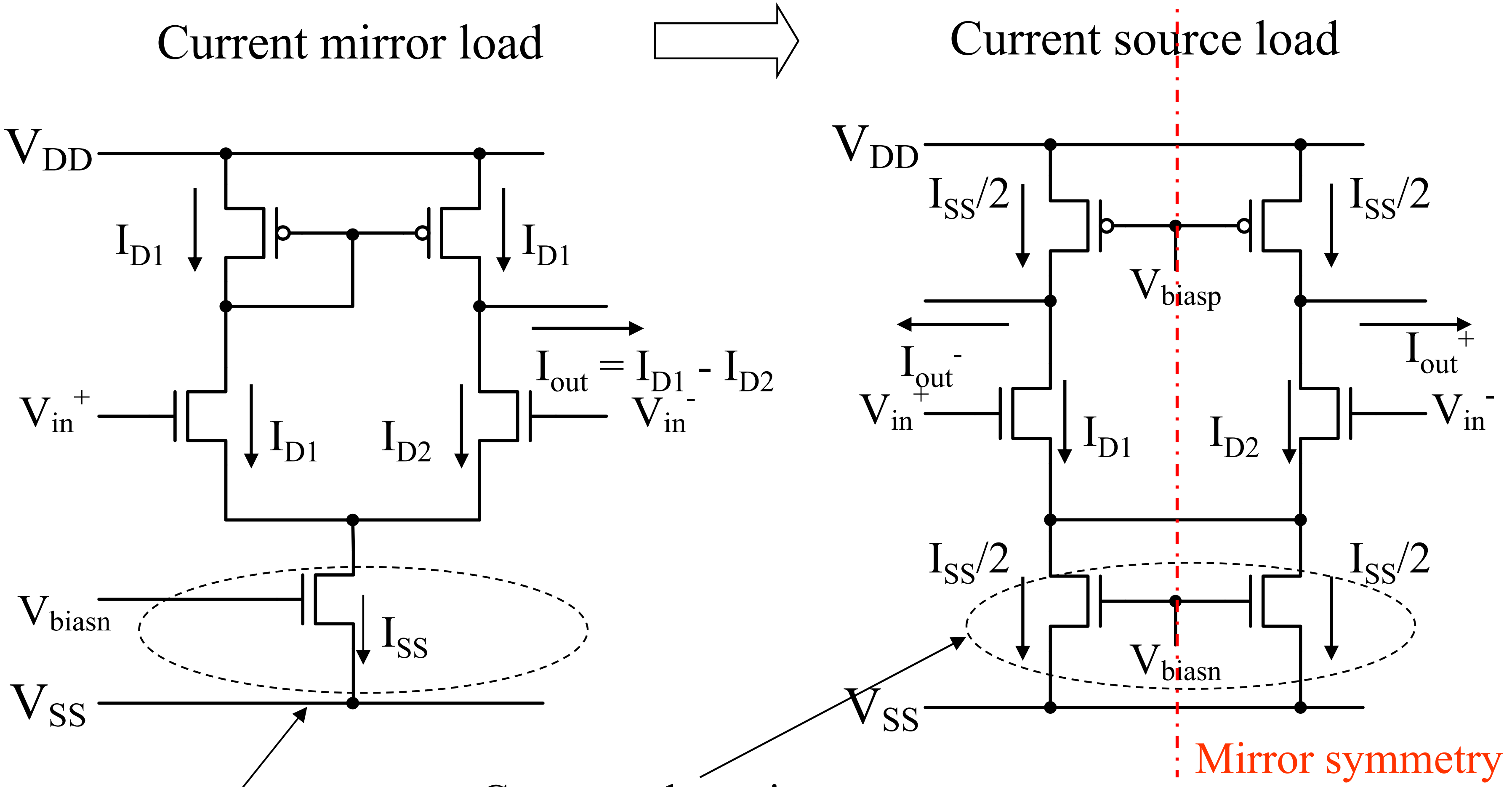
Cancellation of common-mode noise



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 subtraction

common mode rejection

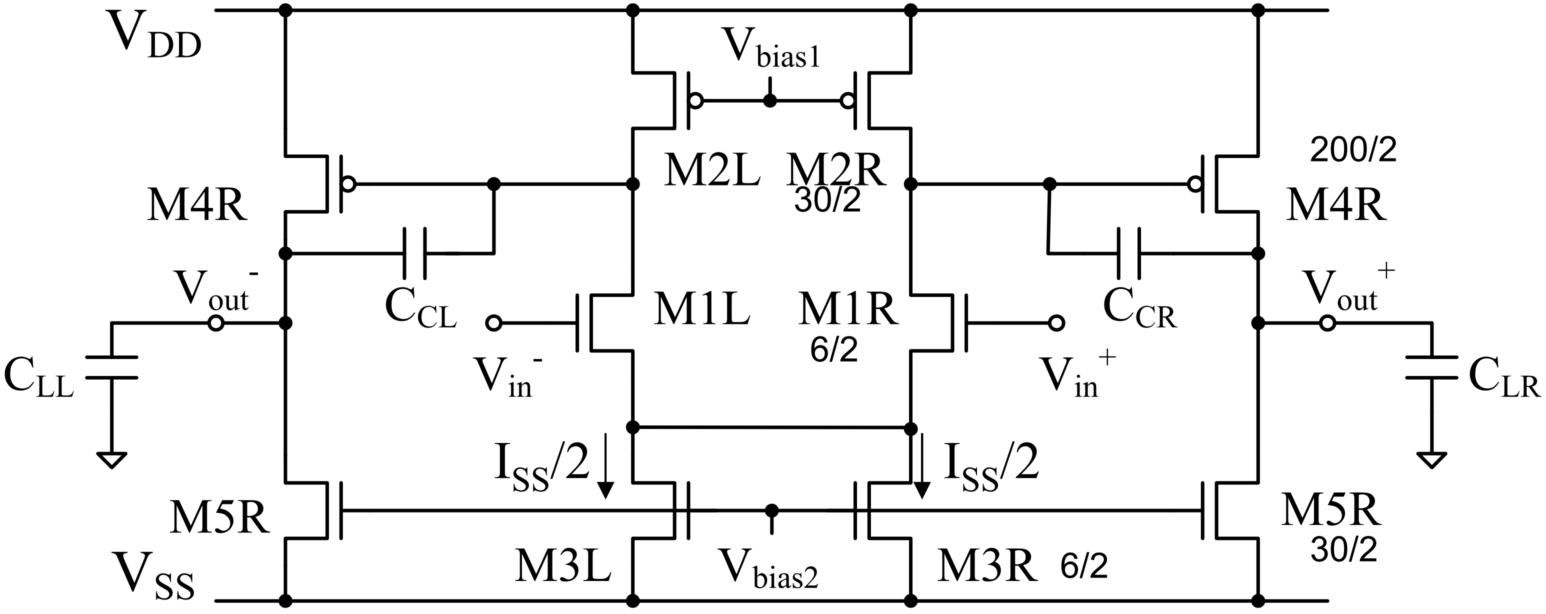
$$I_{SS}/2 = (I_{D1} + I_{D2})/2$$

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

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

13.2 2-stage CS OPA

2-stage CS full-differential OPA



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

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

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

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

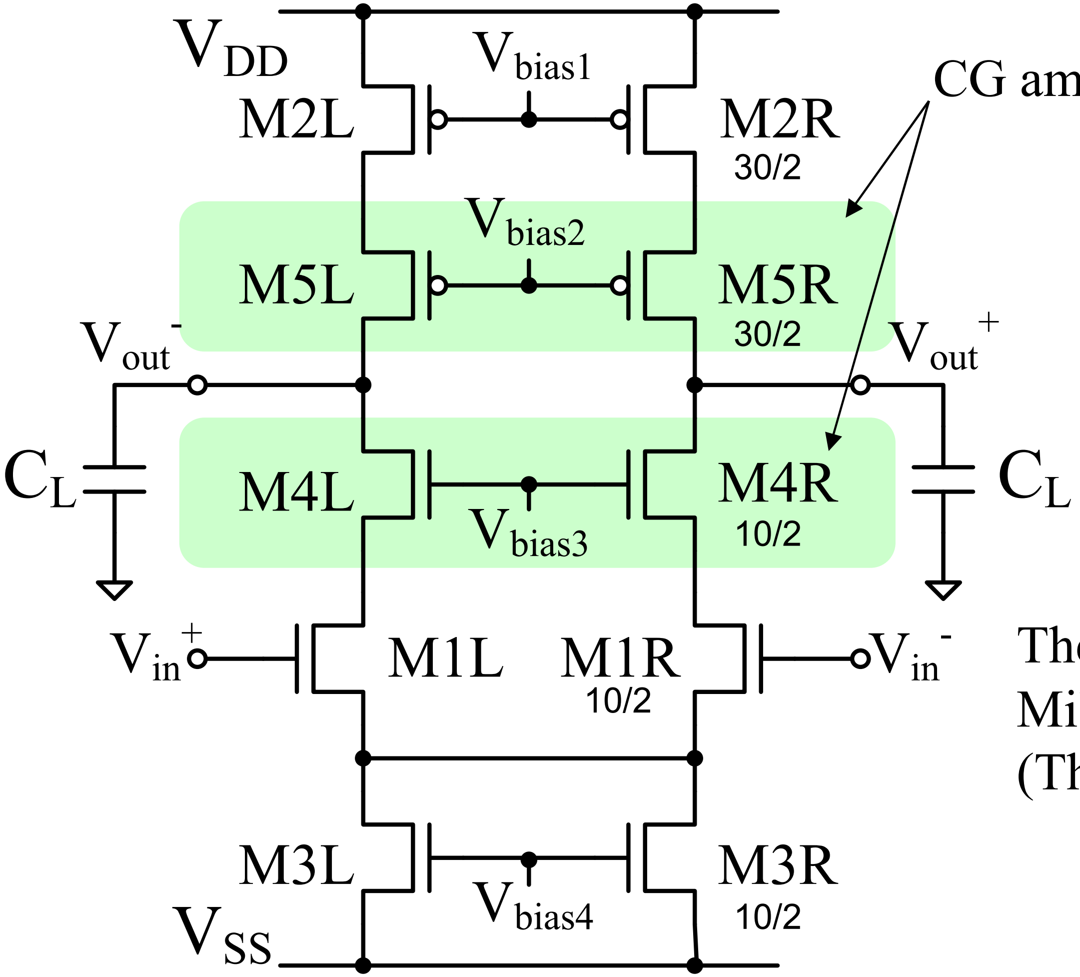
$$\omega_u = \frac{g_{m1}}{C_C}$$

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



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

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

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

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

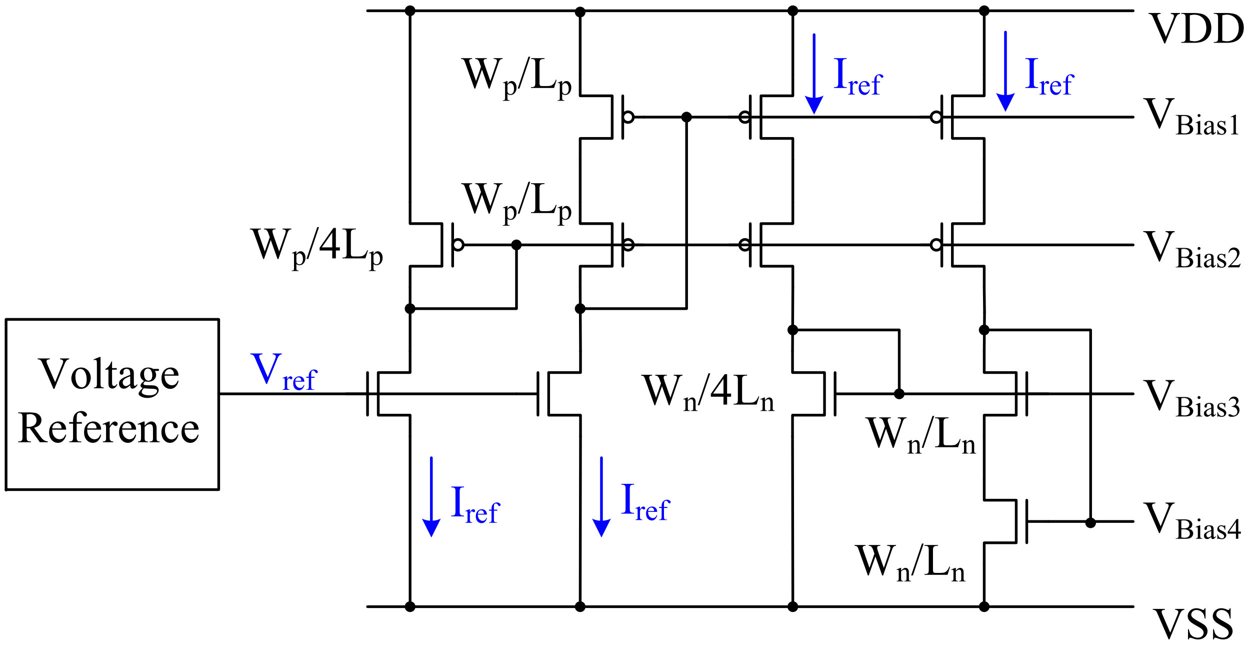
The voltage gain of M1 is about unity and the Miller effect is negligible, thus, $\omega_{p2} \geqq \omega_u$ (The Phase margin depends on the C_L.)

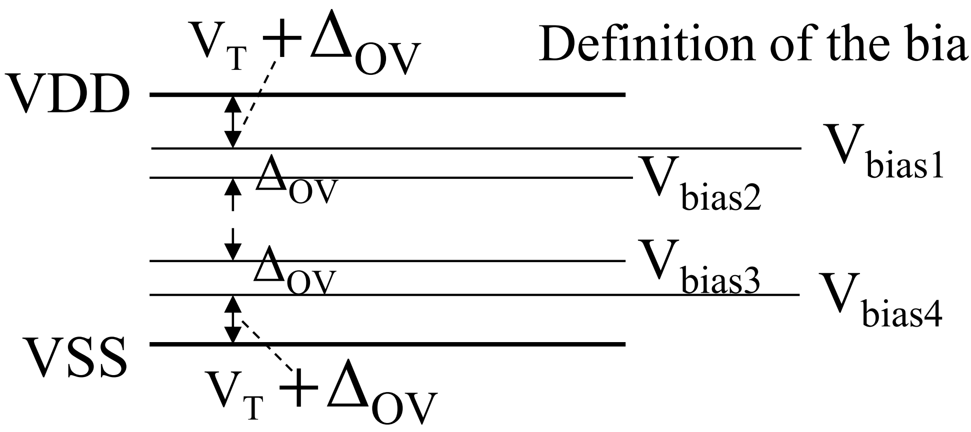
The bias current of M1 and M2 is reused for the M4 and M5.

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

Cascode bias circuit

See Chapter 4, Wide Swing cascode current mirror.



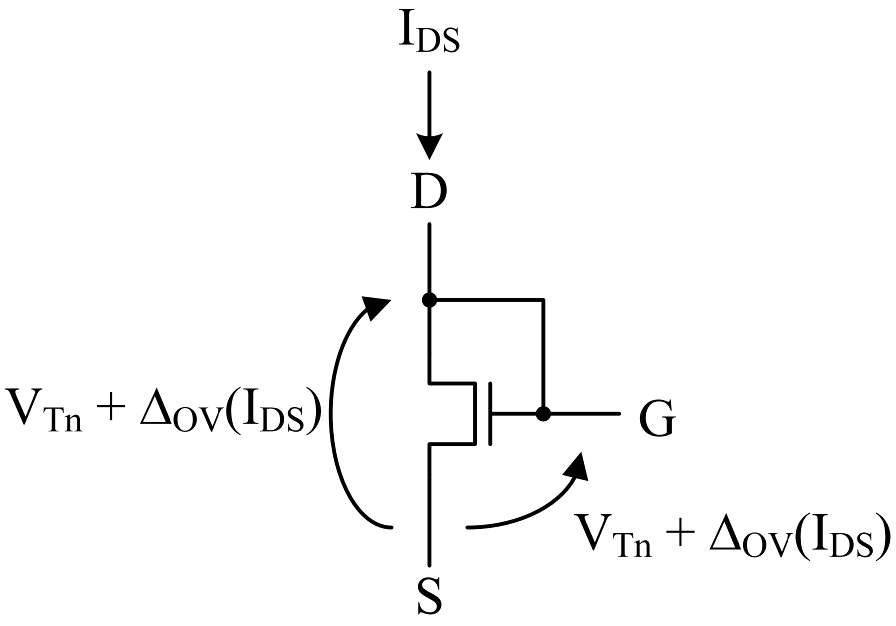


Definition of the bias voltage

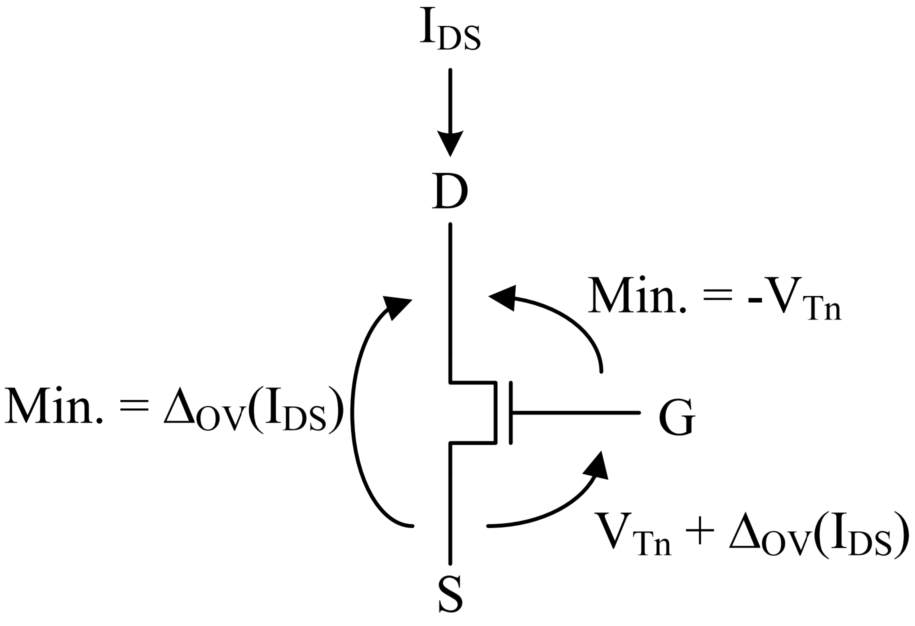
13.4 Folded cascode OPA

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)

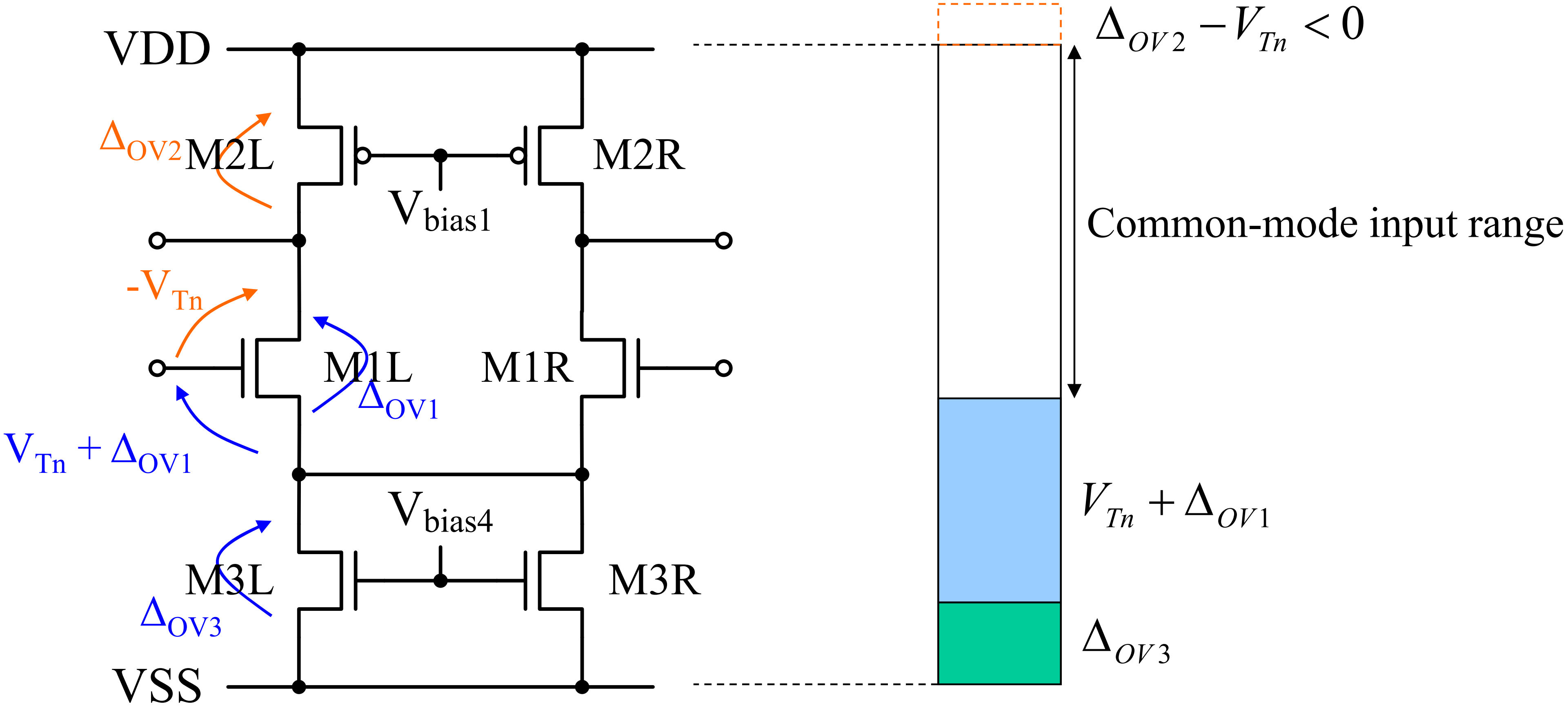


$V_{DS} = V_{GS}$

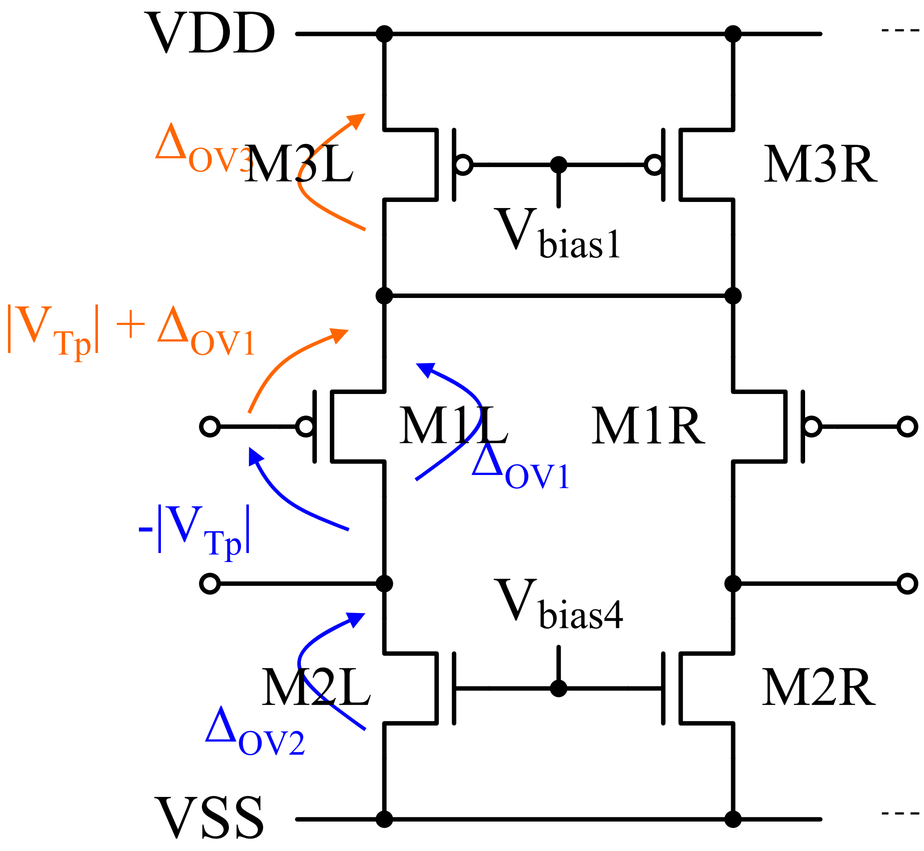


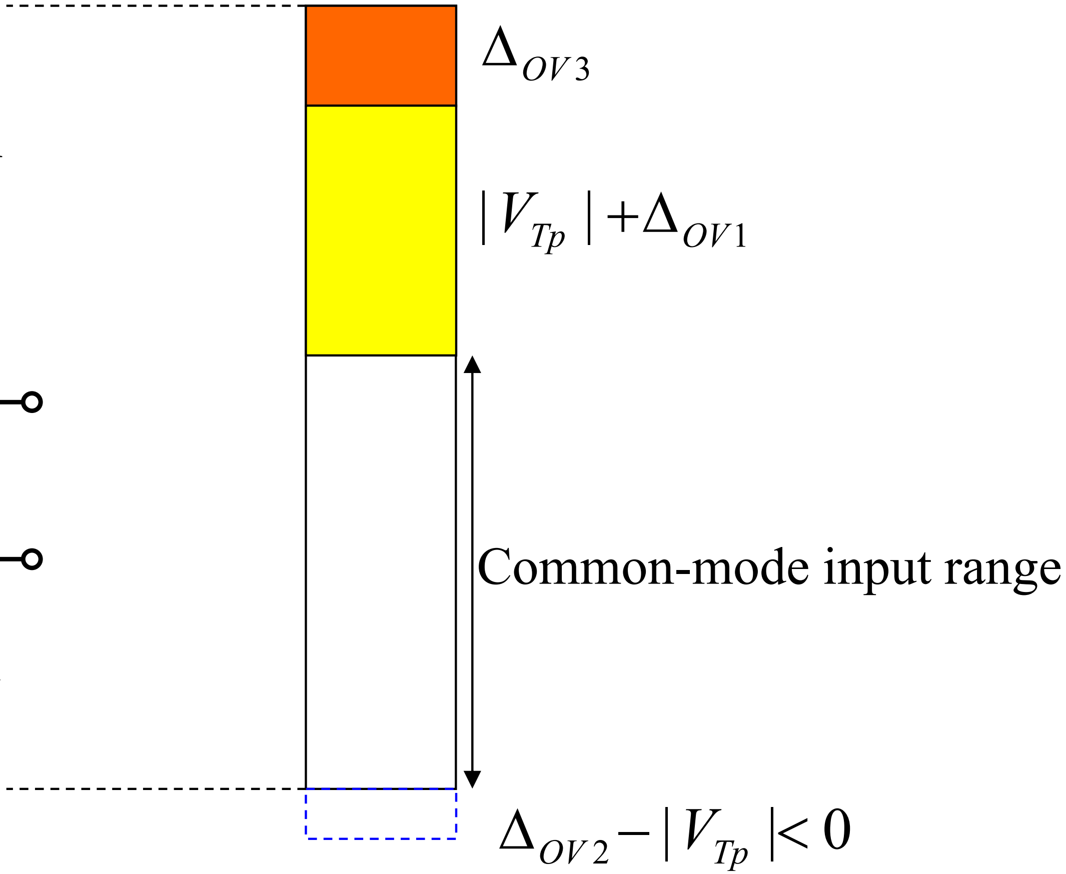
$V_{DS} \neq V_{GS}$

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

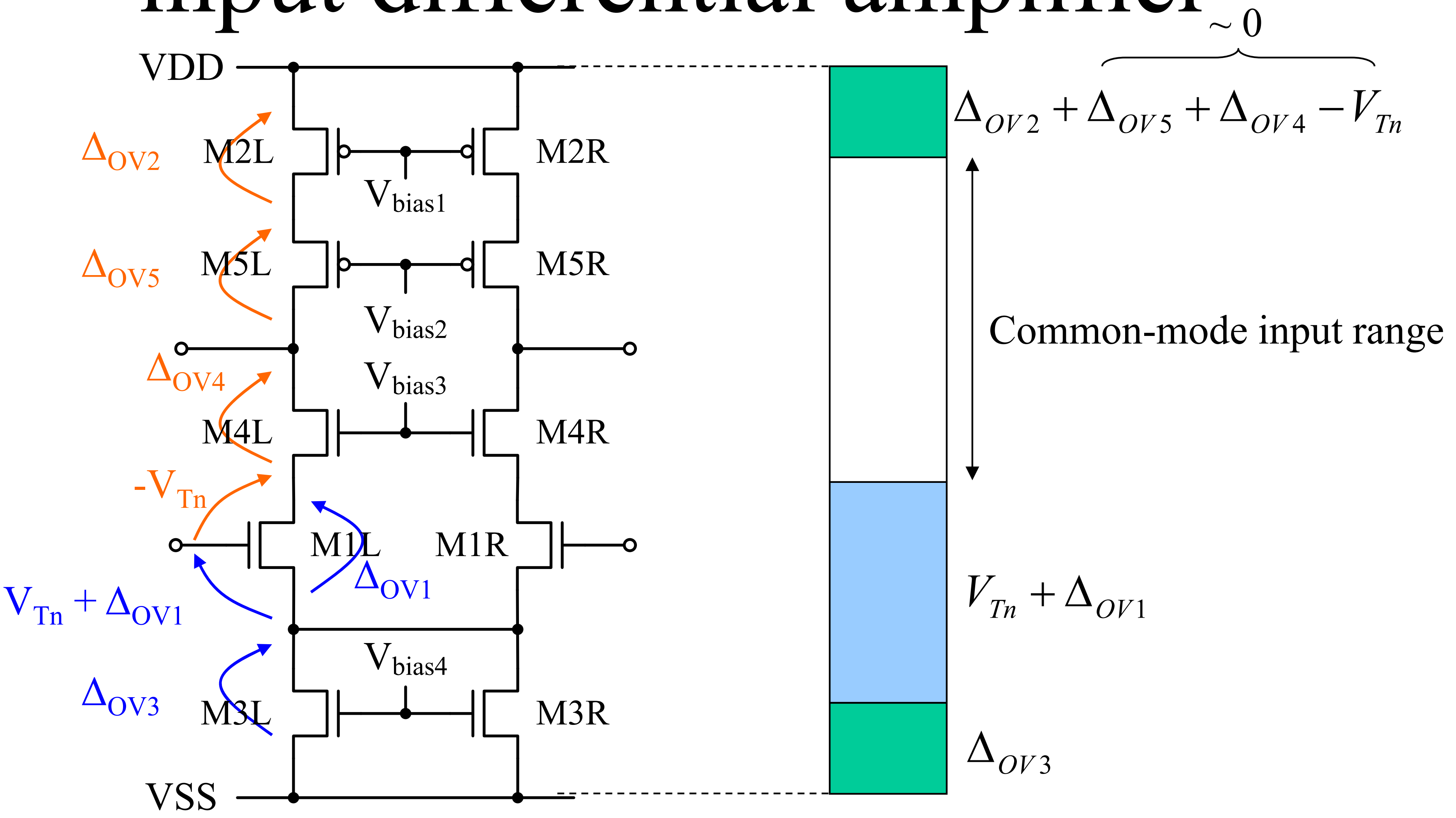


Common-mode input range of p-ch input differential amplifier





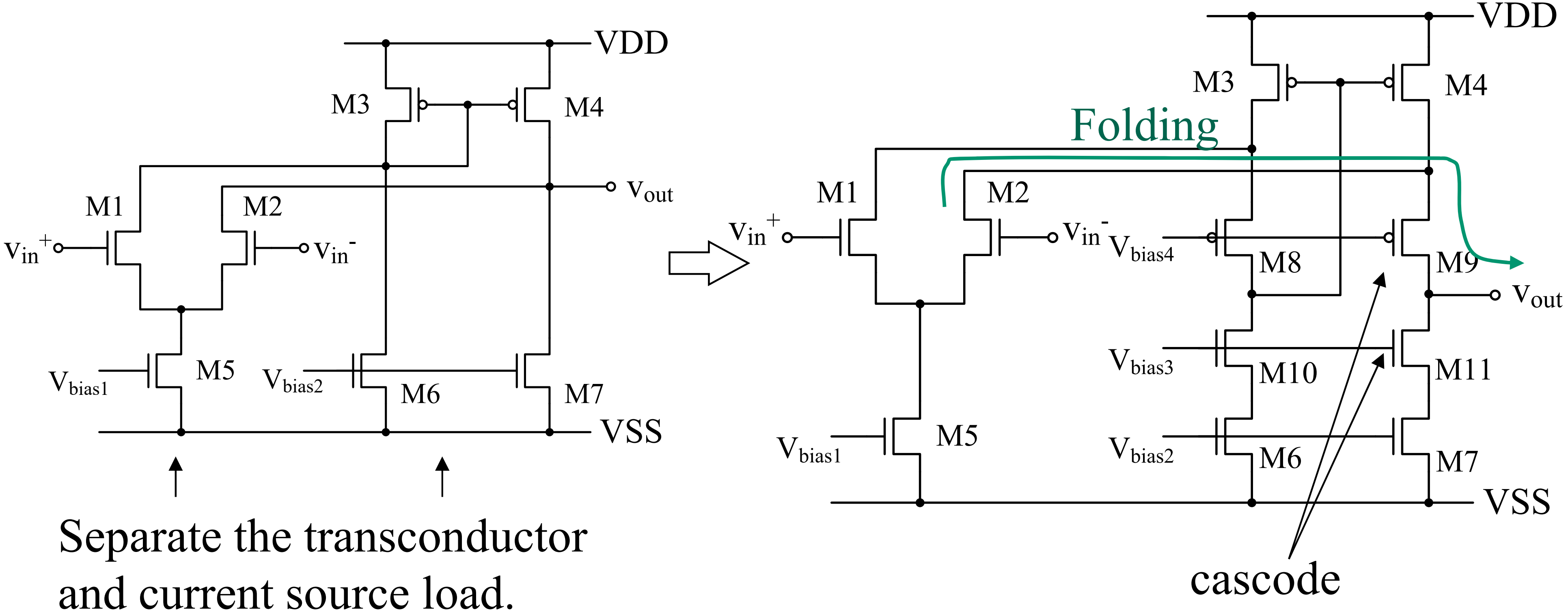
Common-mode input range of n-ch input differential amplifier



High gain, small input range, and small output swing

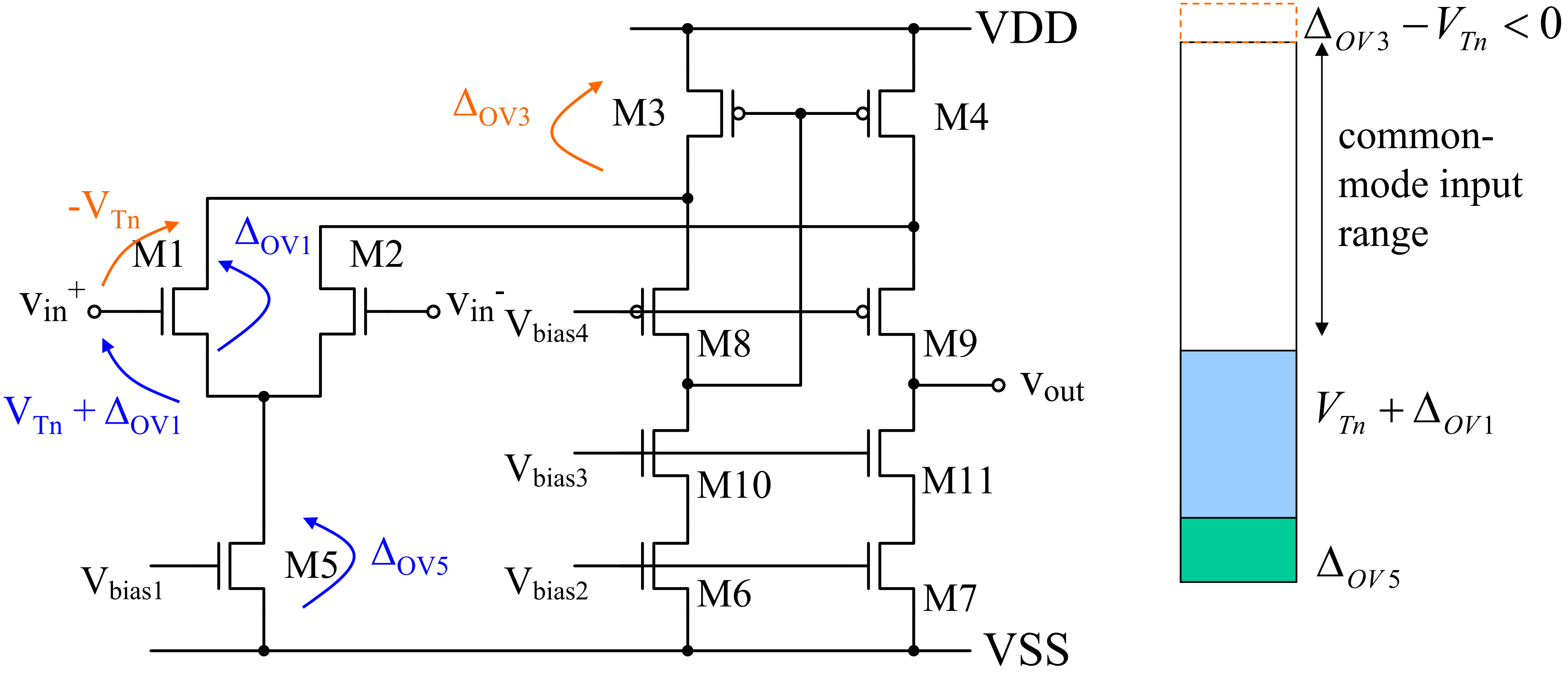
Folding technique of the current source load (single-end)

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

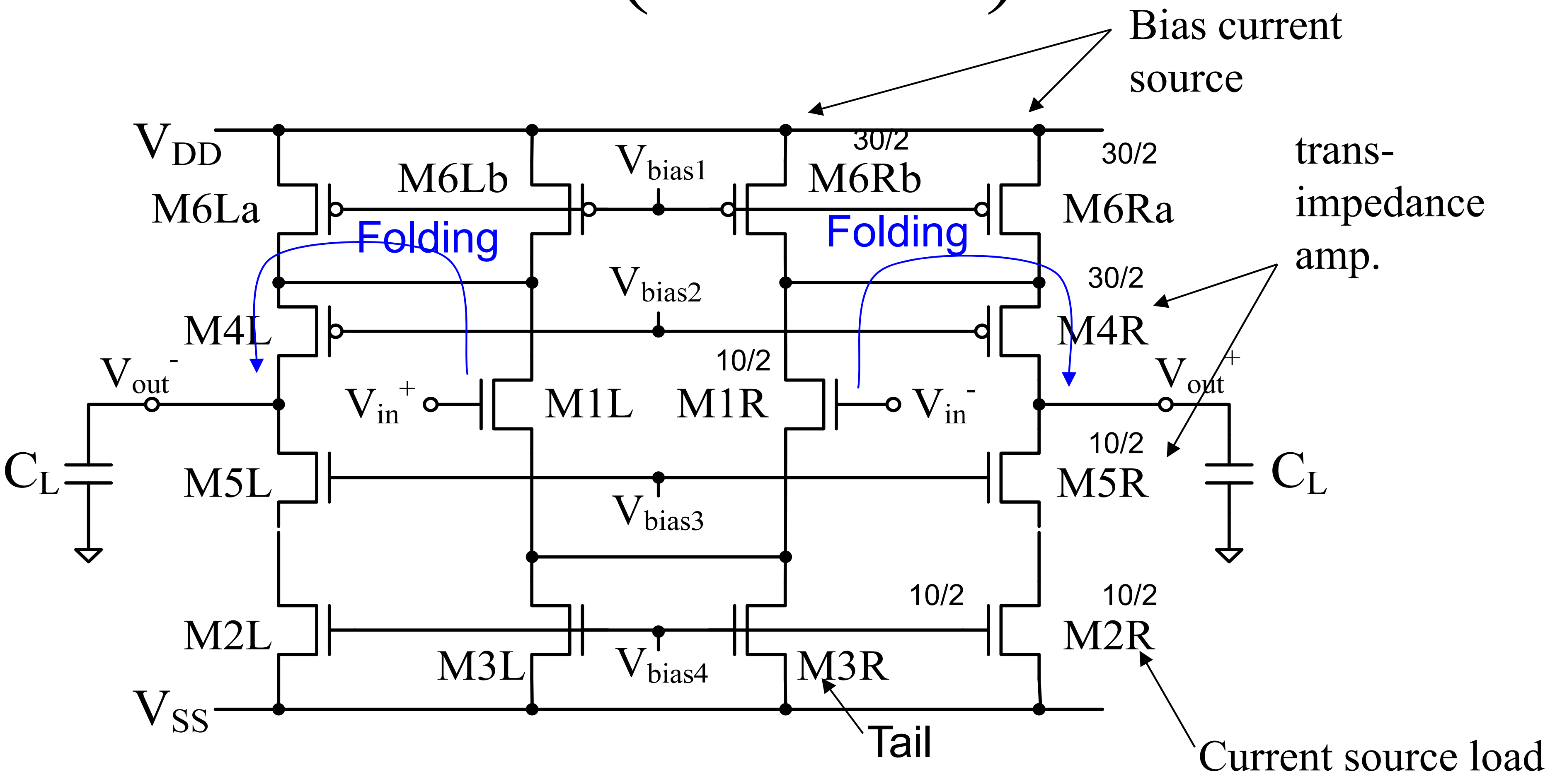


Separate the transconductor and current source load.

Common-mode input range of the folded cascode amplifier



Full-Differential Folded Cascode OPA (or OTA)



Bias current source

trans-impedance amp.

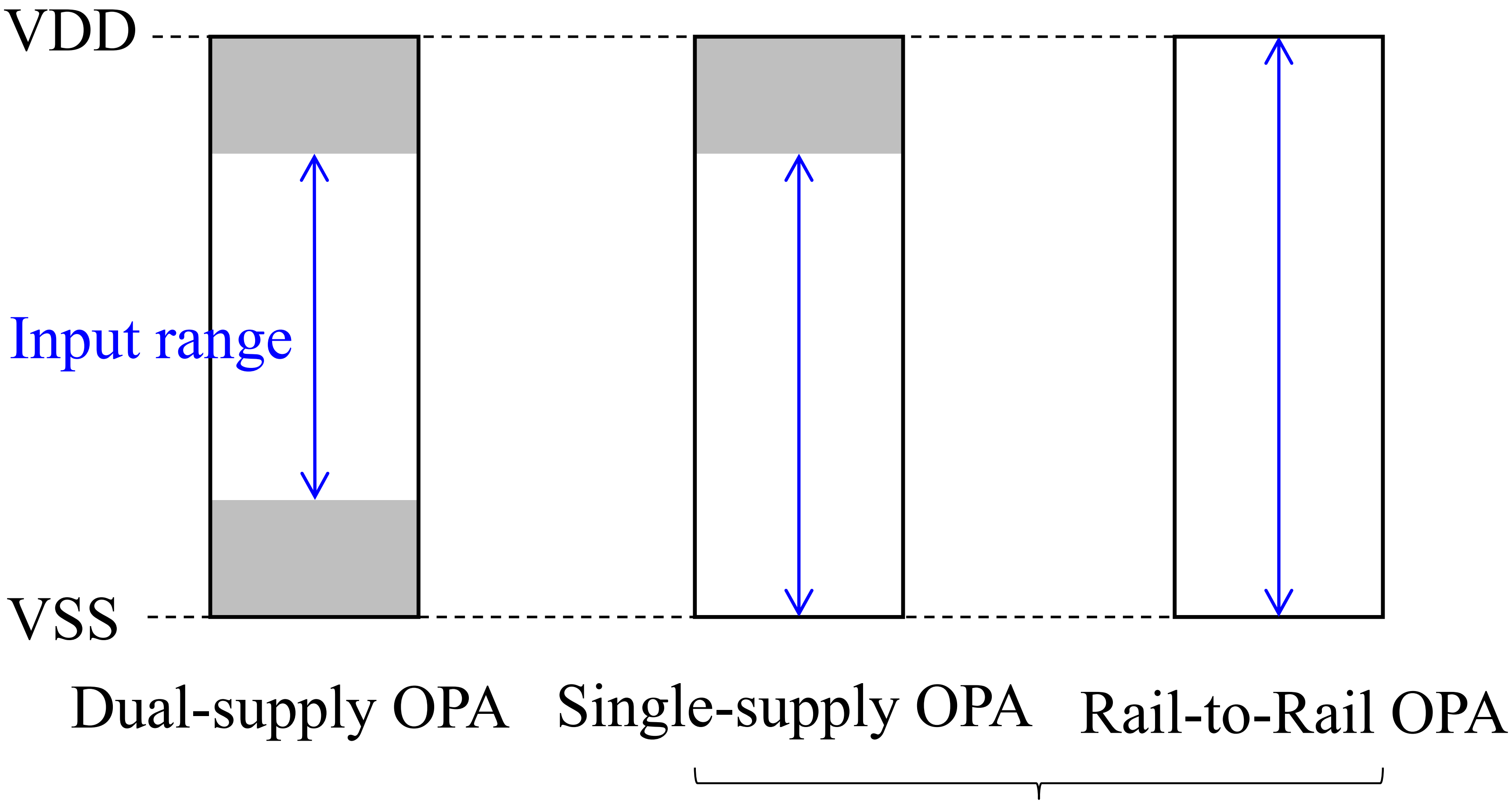
Tail

Current source load

(Same as a circuit shown in previous slide)

13.5 Rail-to-Rail OPA

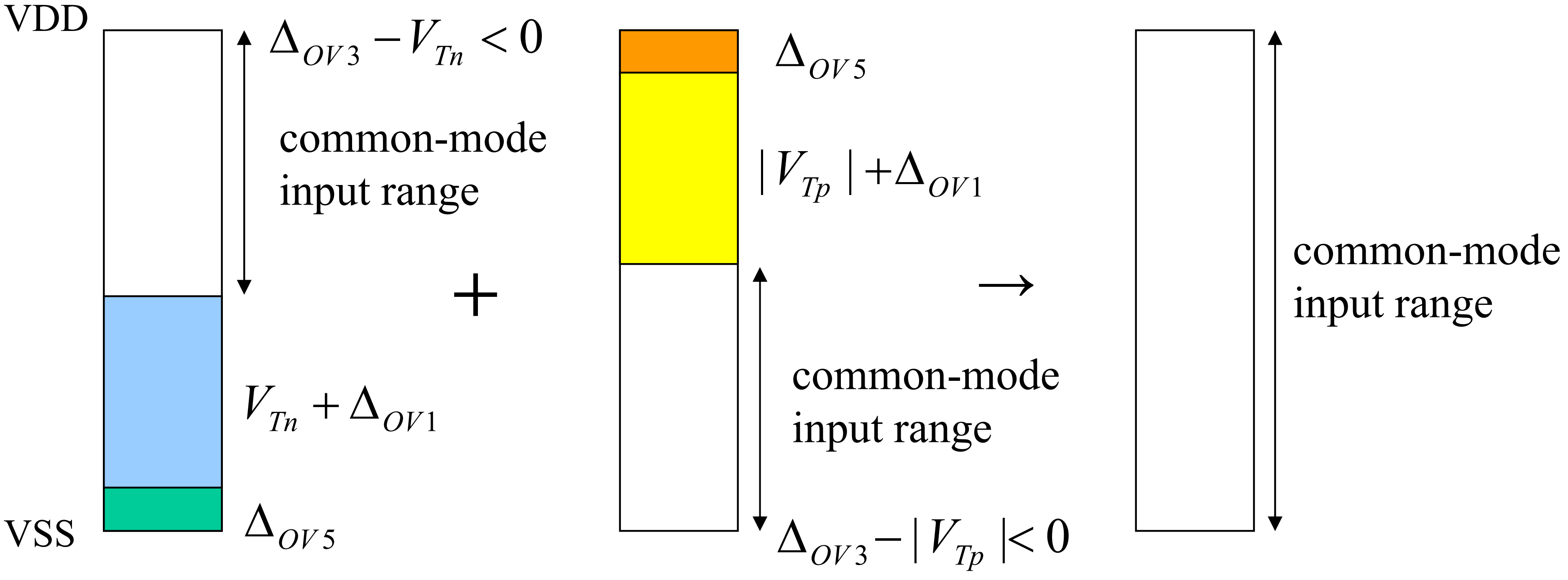
Common mode voltage range of OPA



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

Rail-to-Rail input stage

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



VDD

$\Delta_{OV3} - V_{Tn} < 0$

common-mode input range

$V_{Tn} + \Delta_{OV1}$

VSS

Δ_{OV5}

n-ch input

+

Δ_{OV5}

$|V_{Tp}| + \Delta_{OV1}$

common-mode input range

$\Delta_{OV3} - |V_{Tp}| < 0$

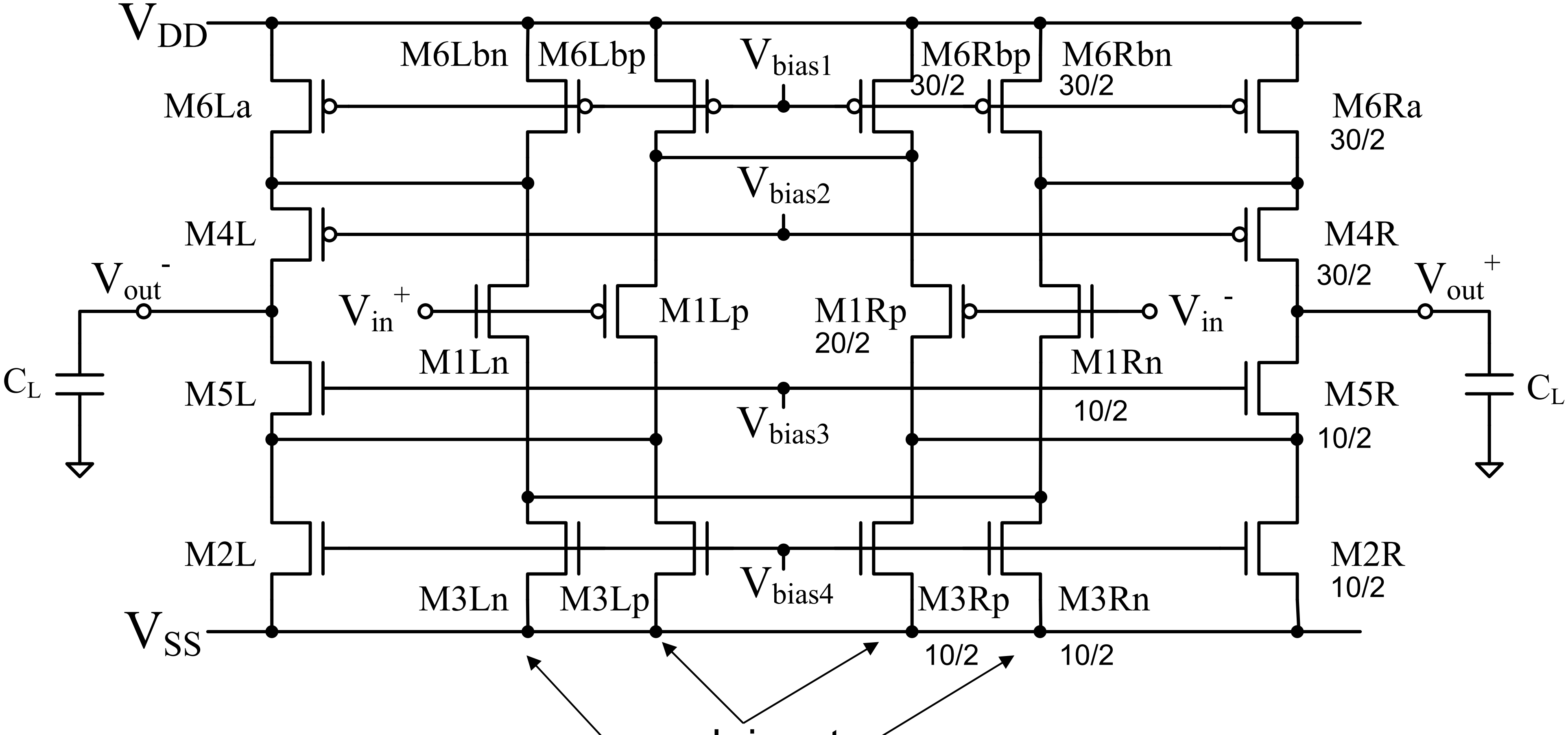
p-ch input

→

common-mode input range

CMOS input

Rail-to-Rail OPA



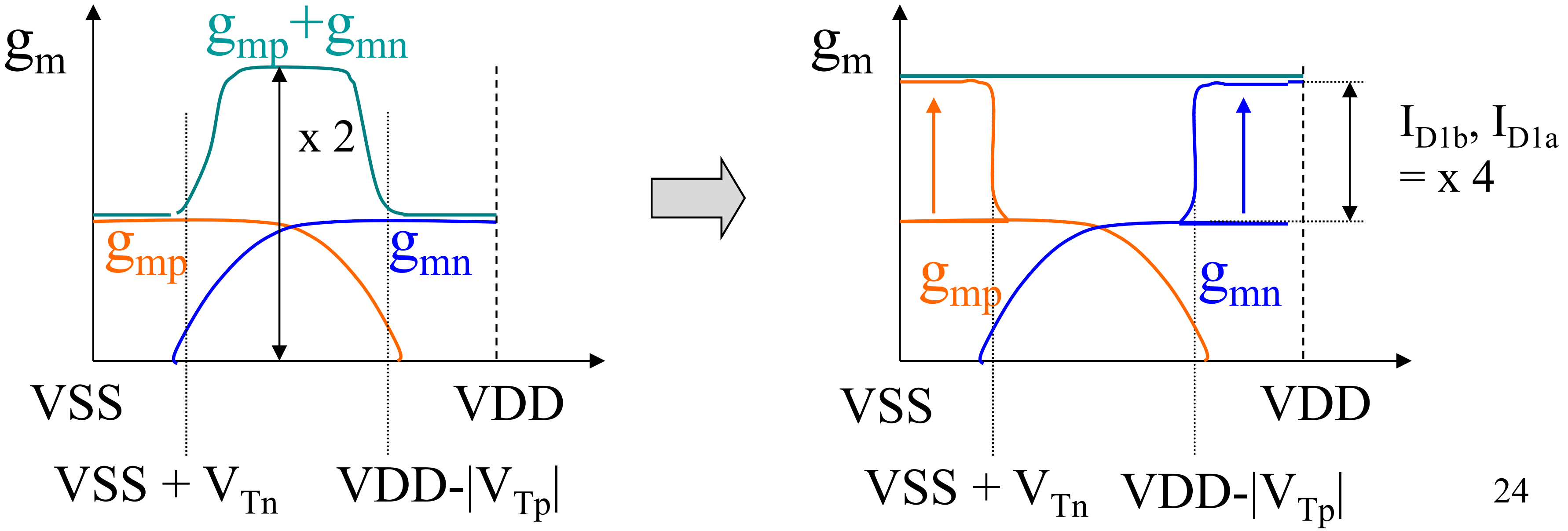
p-ch input

n-ch input

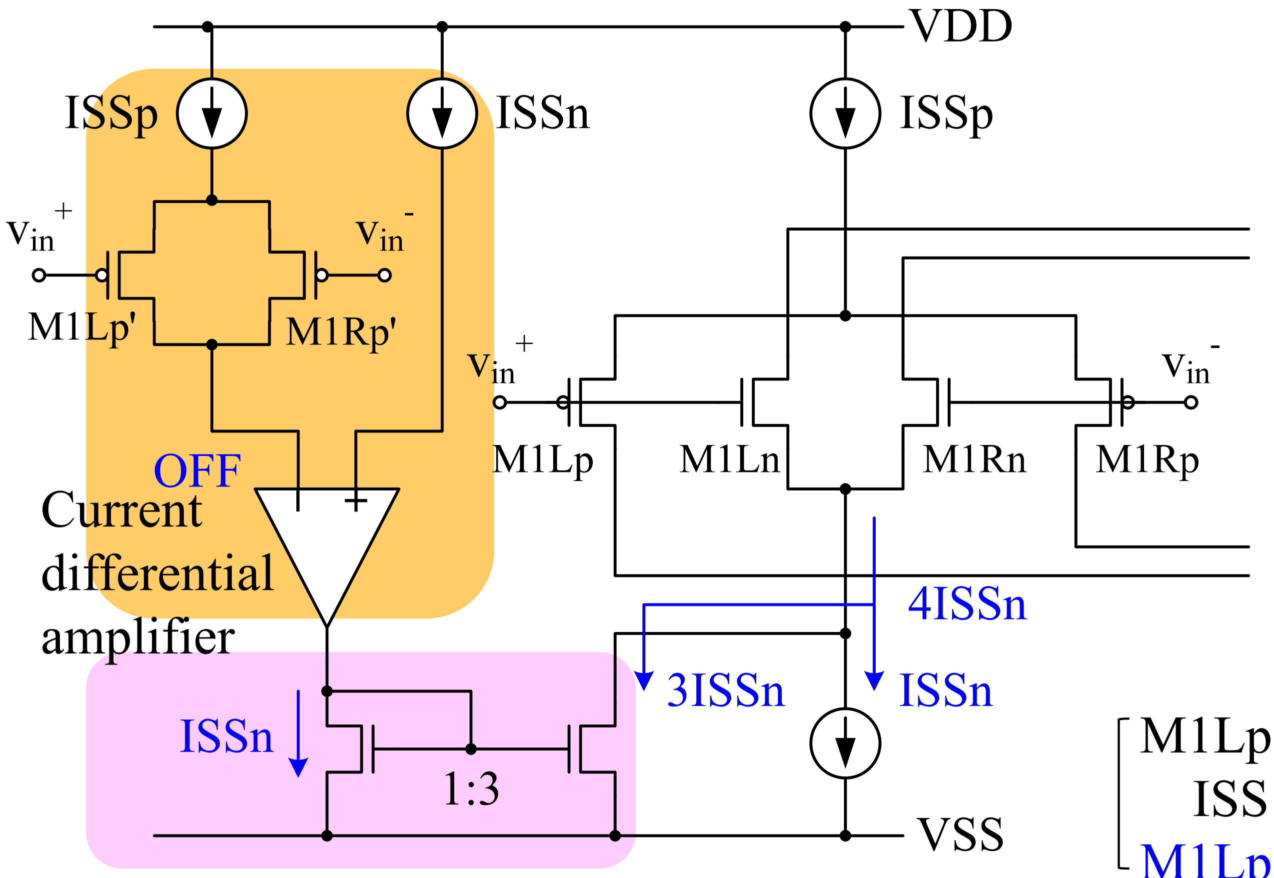
Transconductance uniformity of Rail-to-rail differential amplifier

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

$$\begin{aligned} g_m &= g_{mn} + g_{mp} \\ &= \sqrt{2\beta_{1n} I_{DS1n}} + \sqrt{2\beta_{1p} I_{DS1p}} = \sqrt{2\beta_{1n}} \cdot (\sqrt{I_{DS1n}} + \sqrt{I_{DS1p}}) \end{aligned}$$



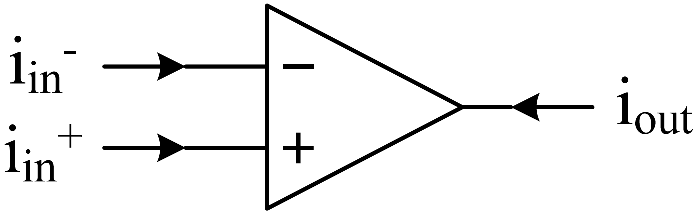
Bias-current control circuit

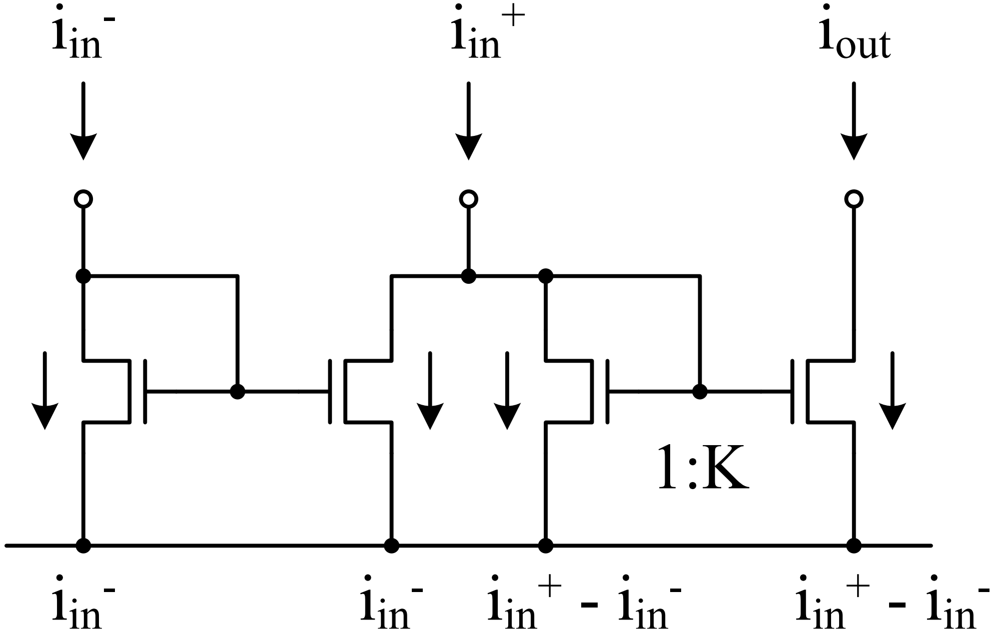


ISSn = ISSp = const.

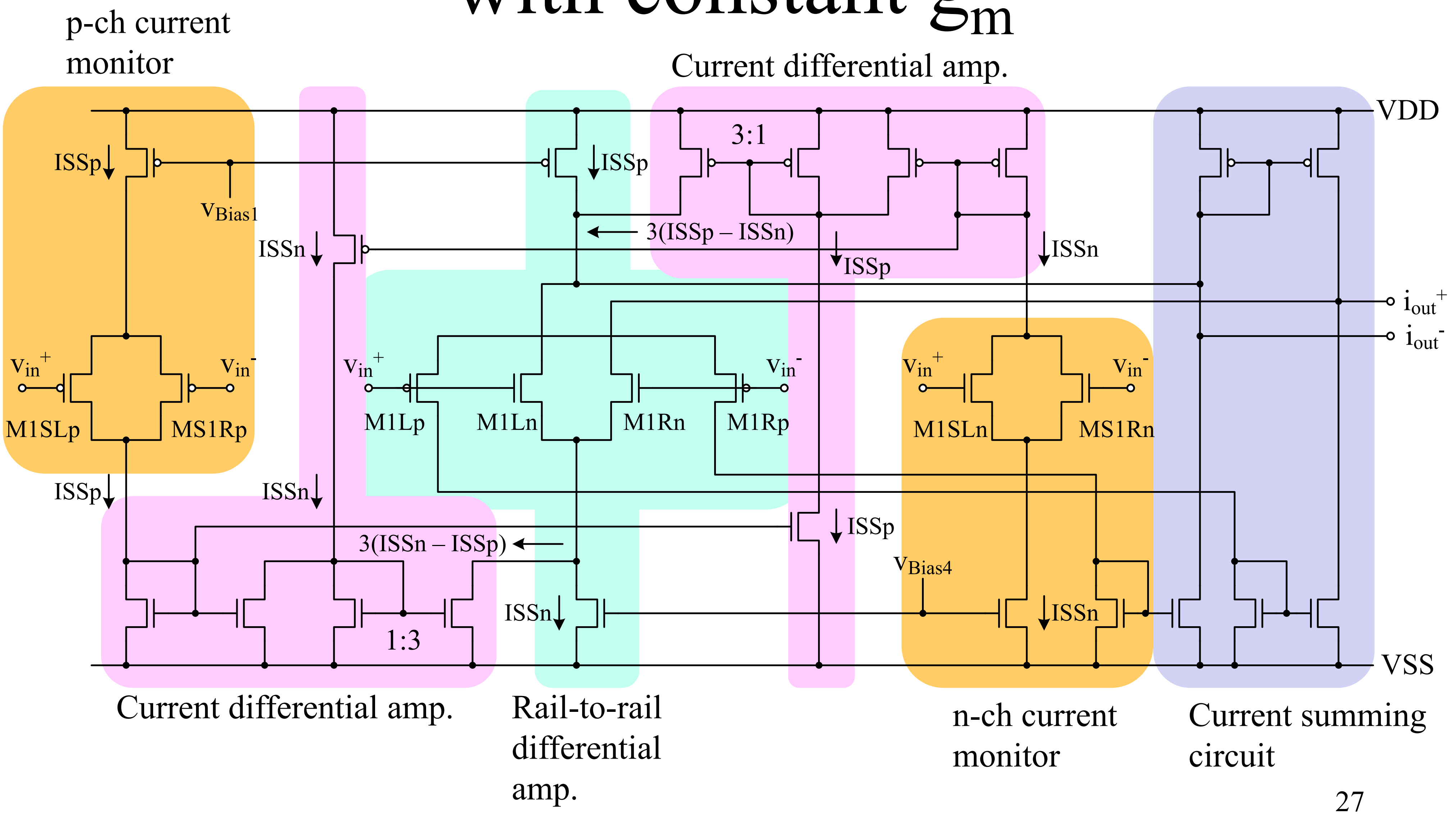
M1Lp', M1Rp' → ON
ISS = 3(ISSn - ISSp) + ISSn = ISSn
M1Lp', M1Rp' → OFF
ISS = 3(ISSn) + ISSn = 4ISSn

Current differential amplifier



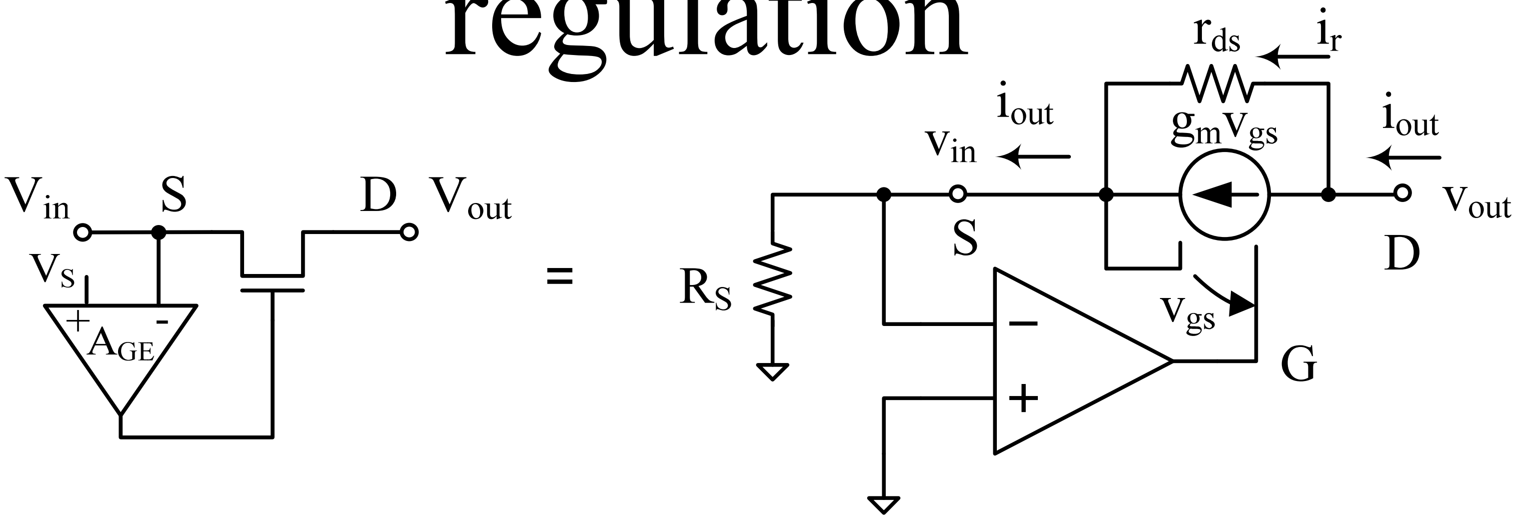


Rail-to-rail differential amplifier with constant g_m



13.6 High gain OPA

Gain enhancement by voltage regulation



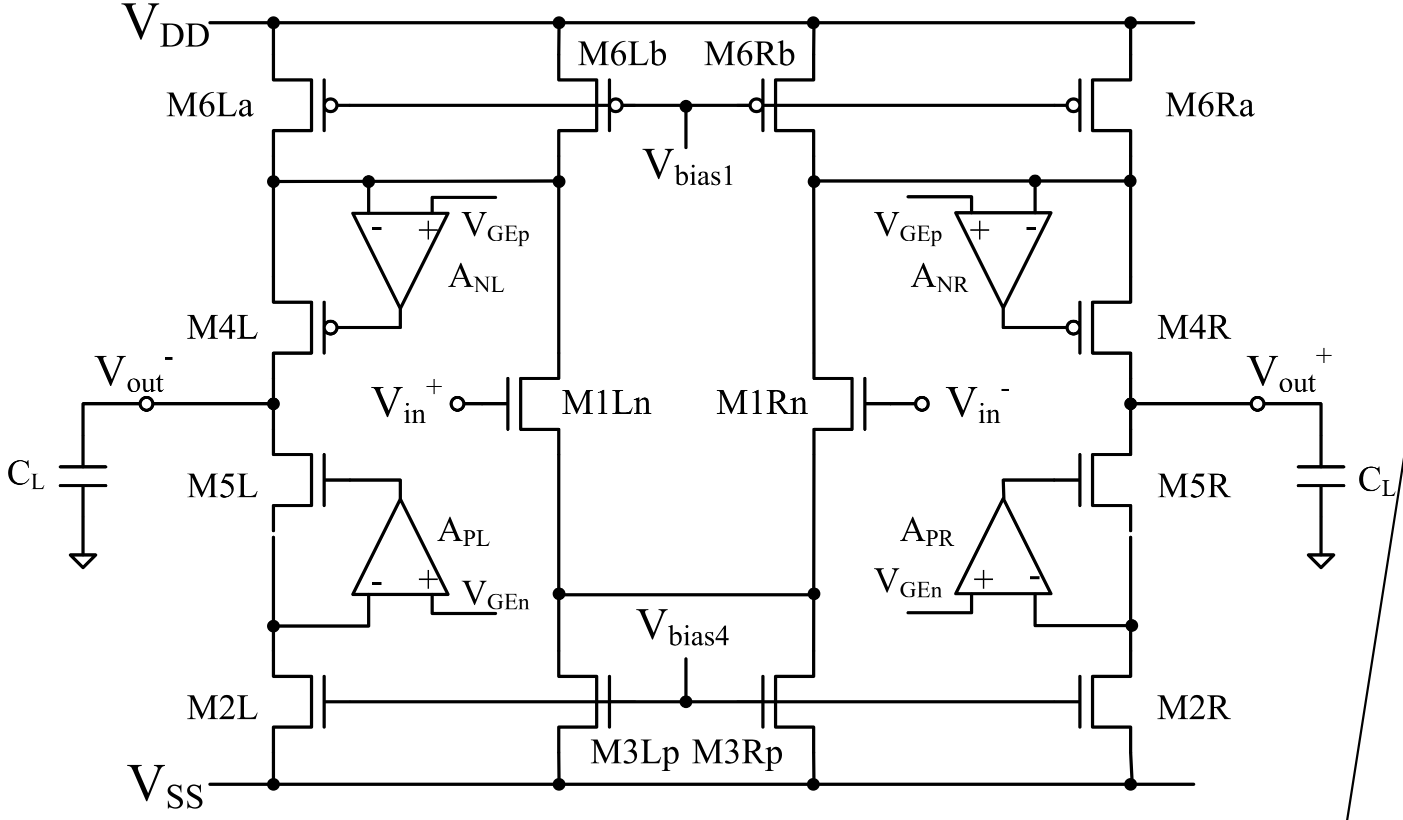
Vin is regulated with NFB.

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

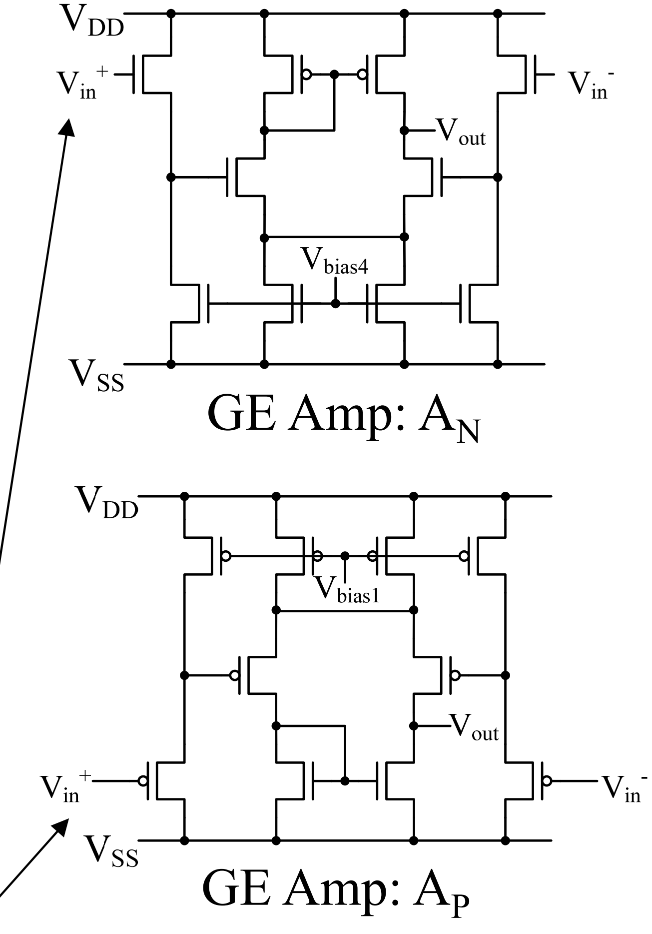
$$R_{out} = \frac{v_{out}}{i_{out}} = r_{ds}(1 + g_m(A_{GE}+1)R_S) + R_S \approx A_V(A_{GE}+1)R_S$$

Folded Cascode OPA with gain enhancement (GE) amplifiers

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



GE amplifiers

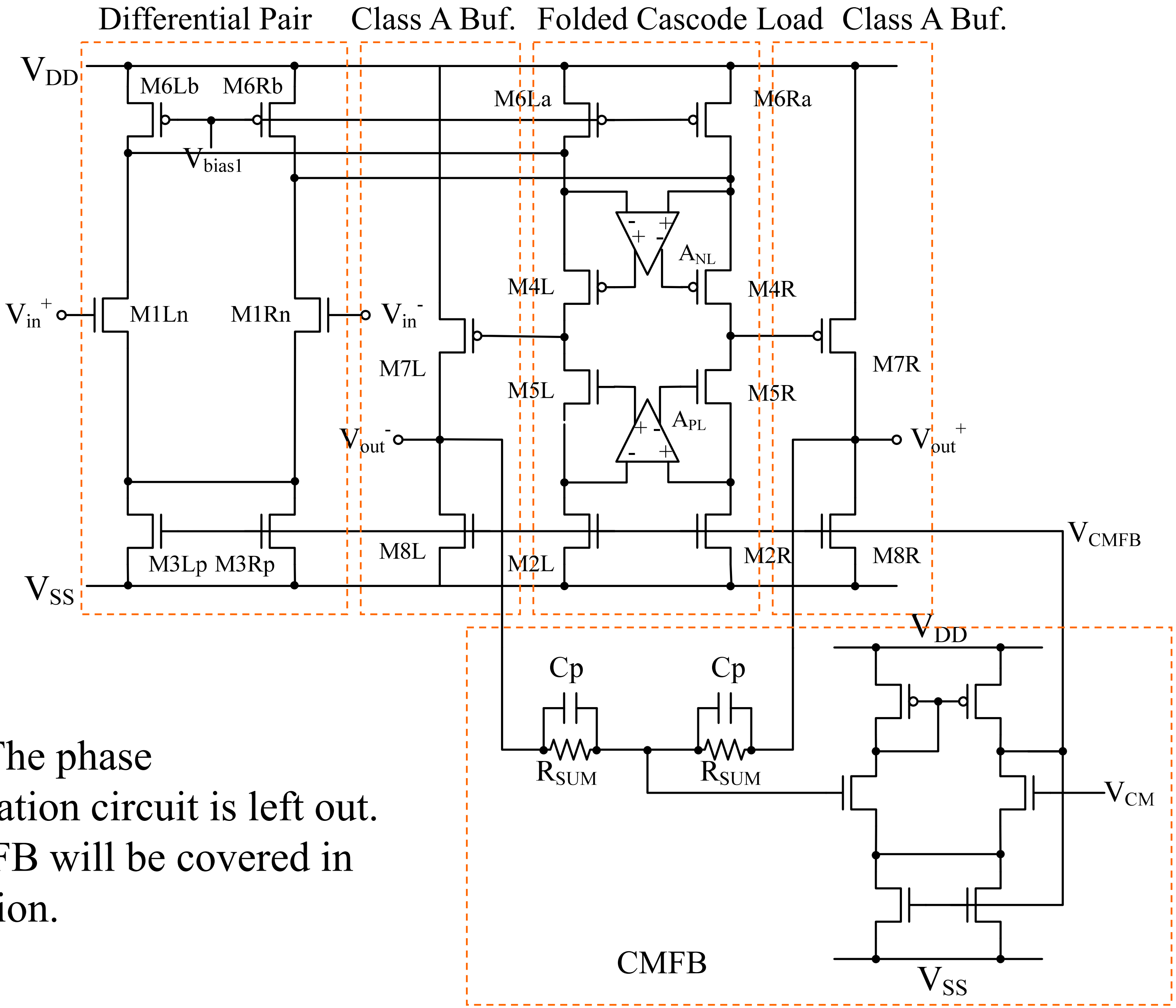


GE Amp: A_N

GE Amp: A_P

Source follower input (Level shifter)

Design example of GE-FC-OPA

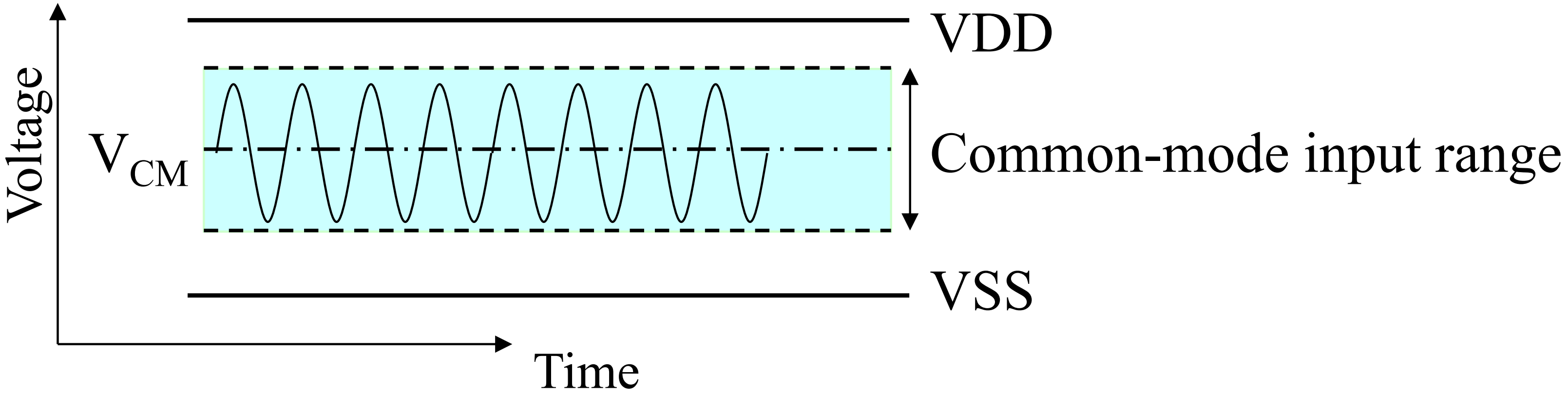


NOTE: The phase compensation circuit is left out. The CMFB will be covered in next section.

13.7 Common mode feedback

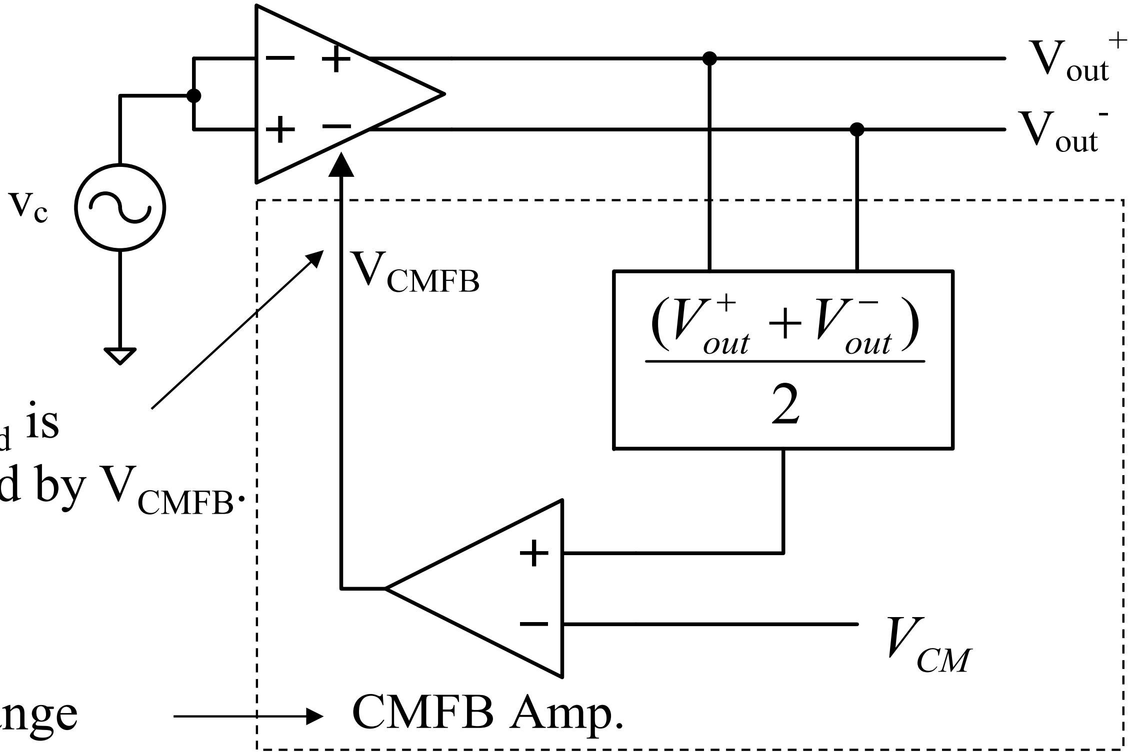
Common Mode Feedback (CMFB)

- 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,
  - $I_{load\_L} + I_{load\_R} > I_{SS} \rightarrow \quad V_{out}^{+} = V_{out}^{-} = VDD$
  - $I_{load\_L} + I_{load\_R} < I_{SS} \rightarrow \quad V_{out}^{+} = V_{out}^{-} = VSS$



Operation of CMFB

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

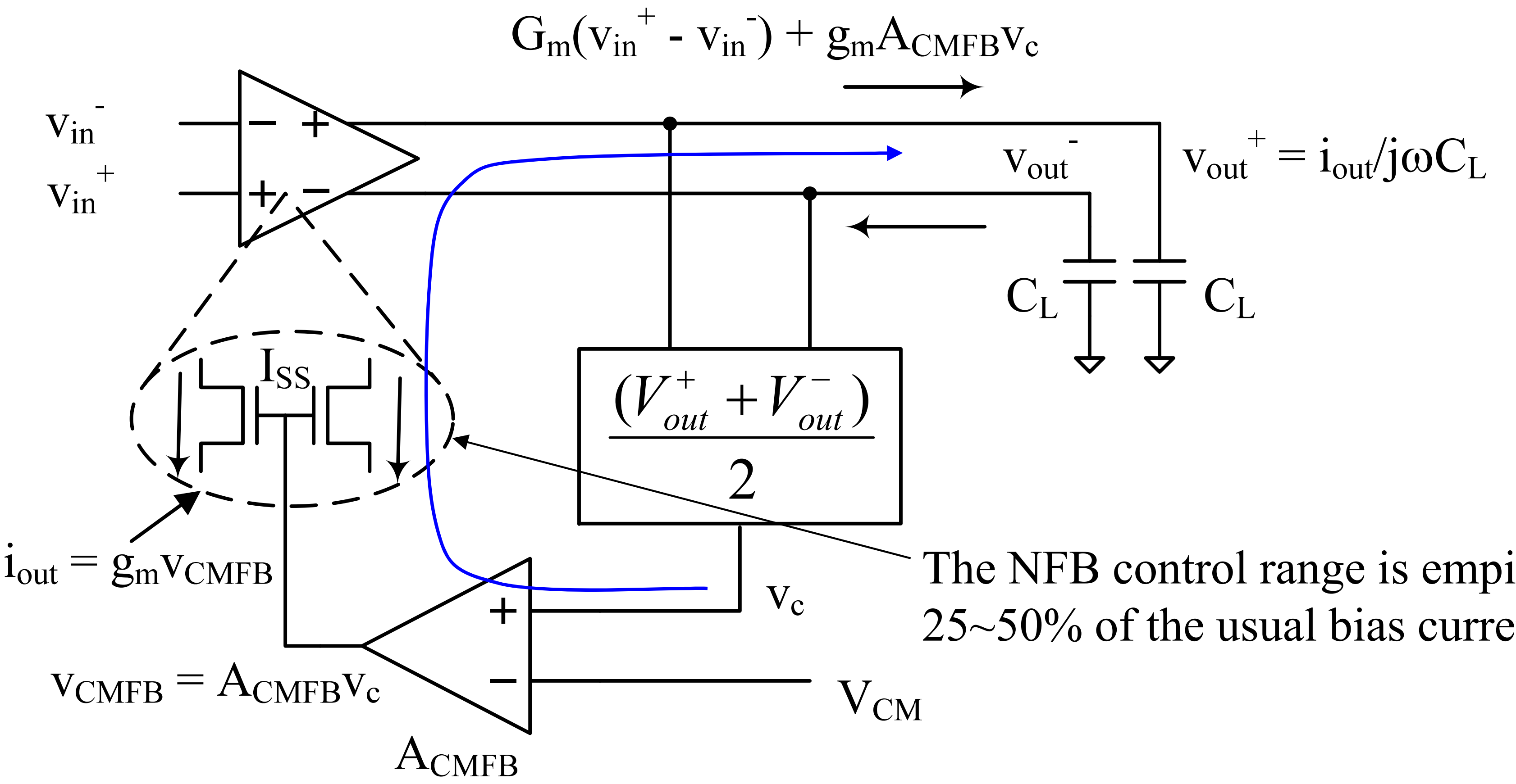


I_{SS} or I_{load} is
controlled by V_{CMFB}.

Wide input range
differential amplifier

CMFB circuit

Loop gain of CMFB amplifier



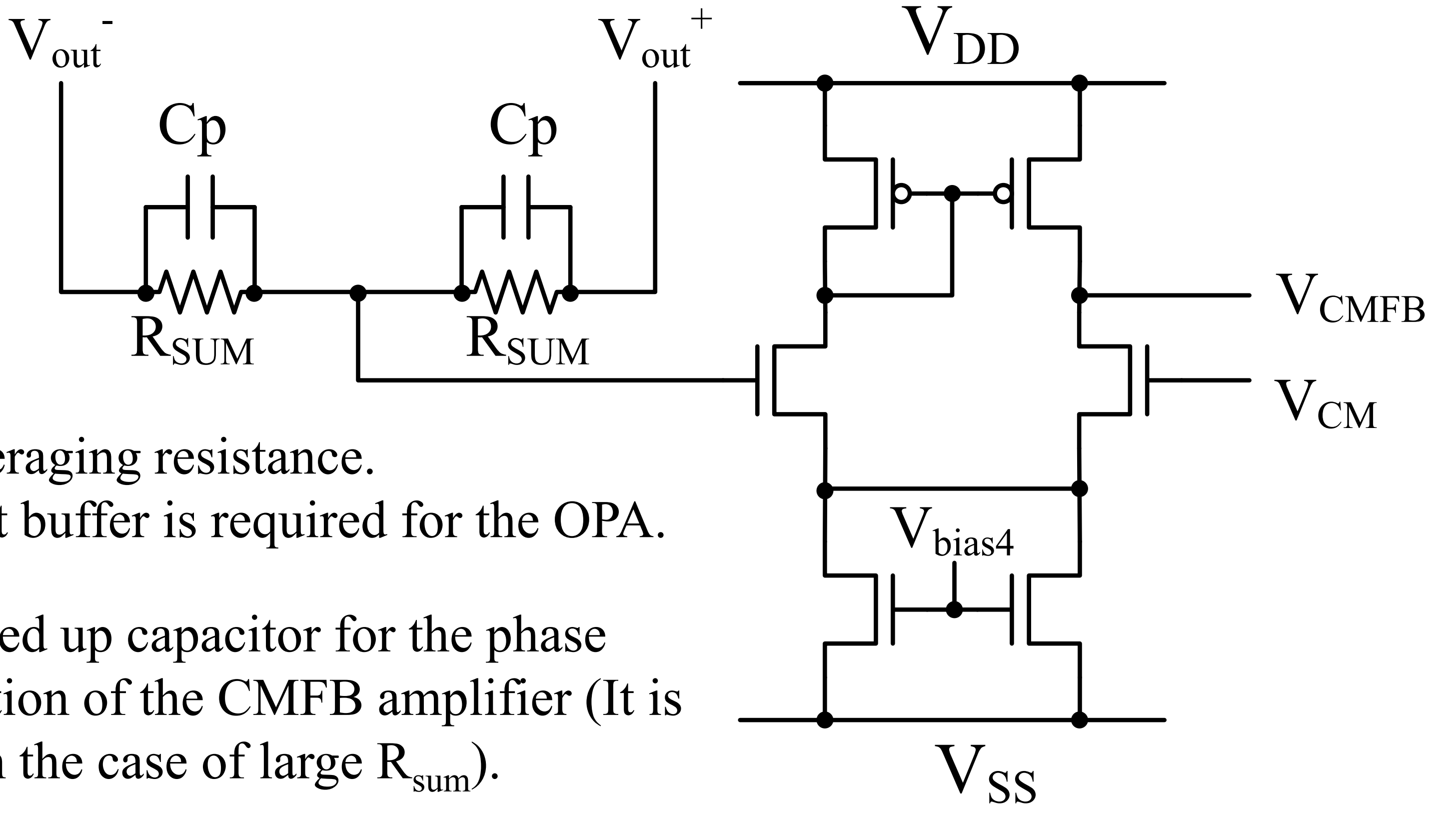
The NFB control range is empirically 25~50% of the usual bias current.

Unity gain frequency of CMFB loop gain

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

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

CMFB circuit for continuous-time OPA (1)

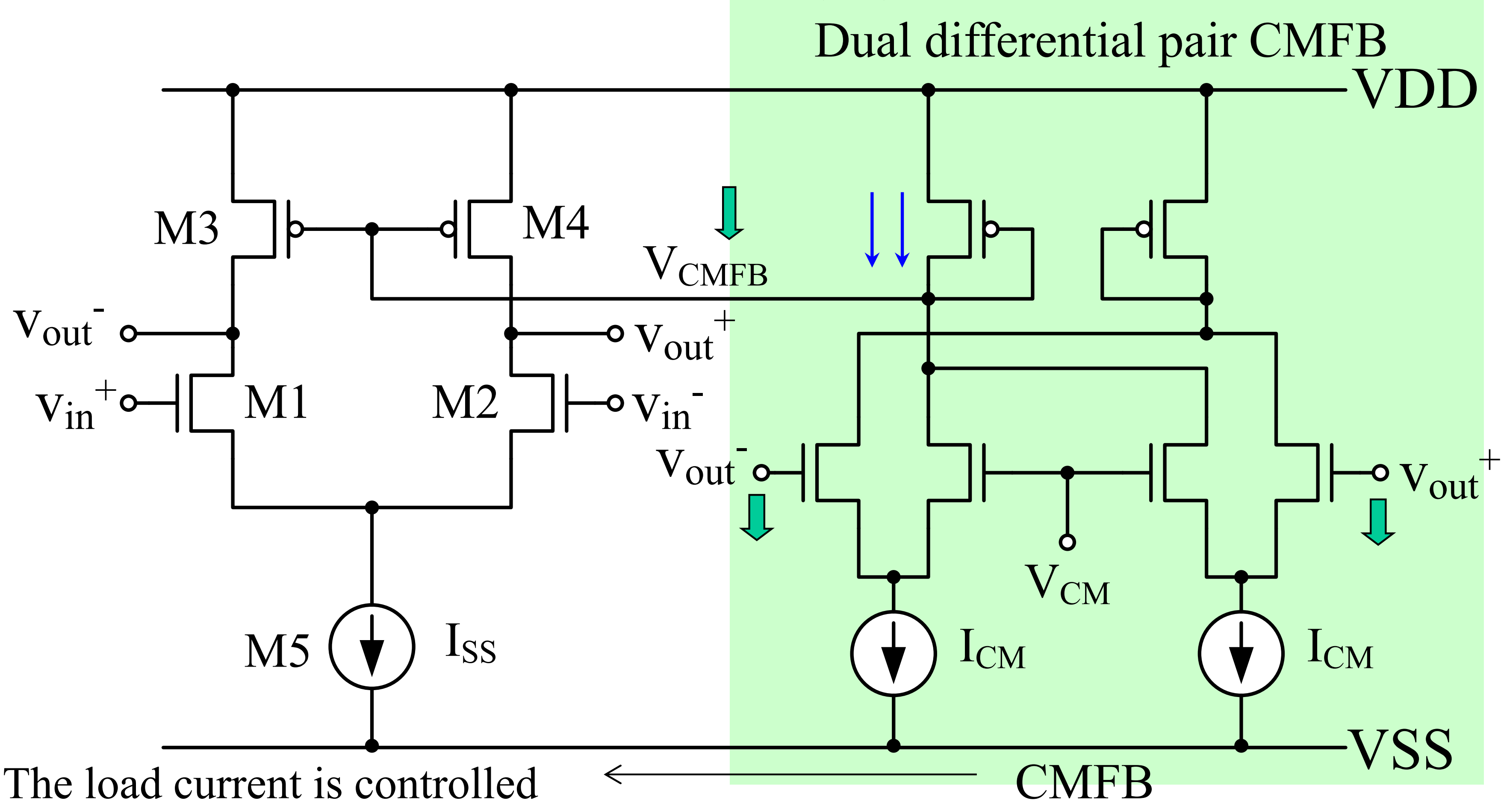


R_{sum} is averaging resistance.
The output buffer is required for the OPA.

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

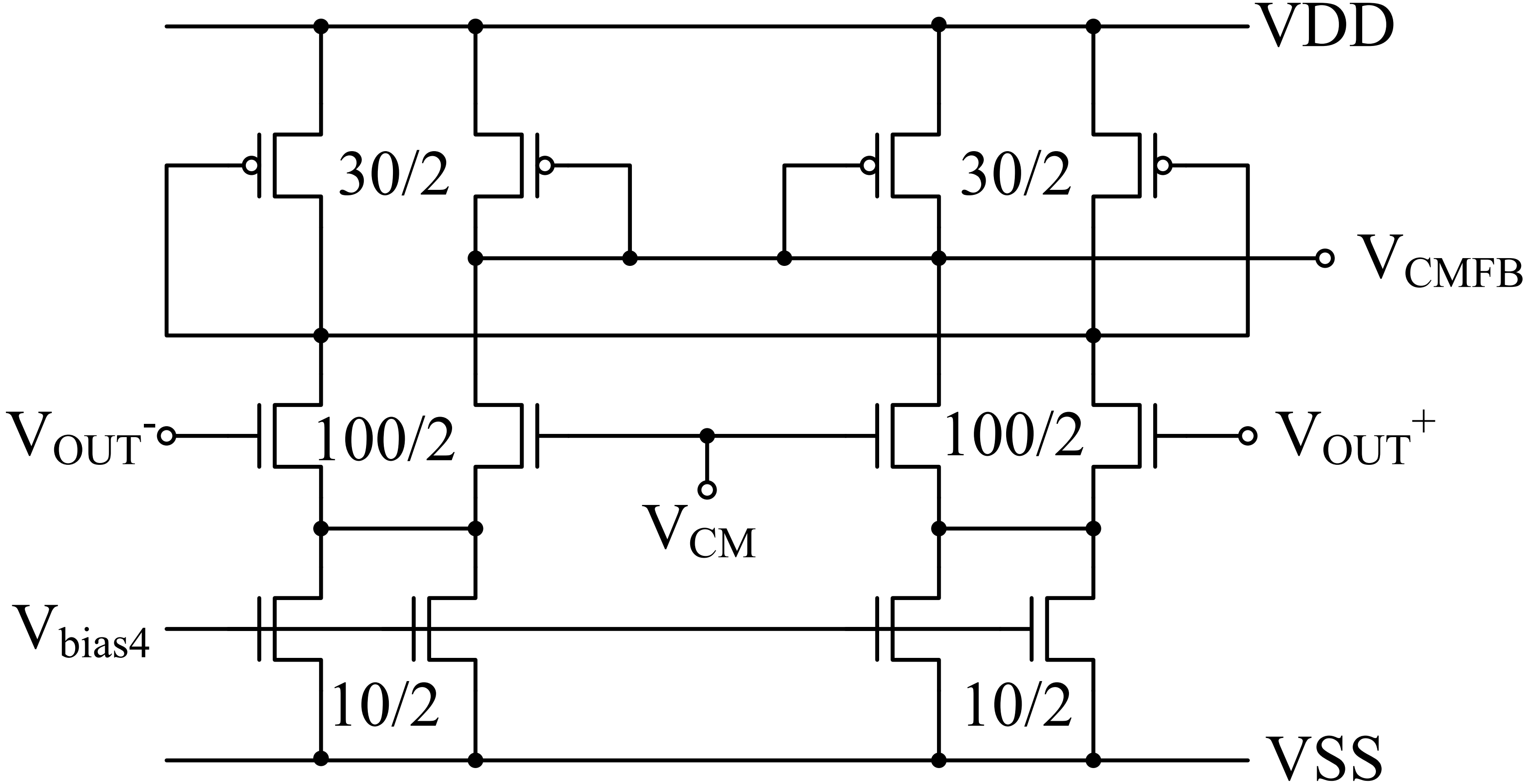
CMFB circuit for continuous-time OPA (2)



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

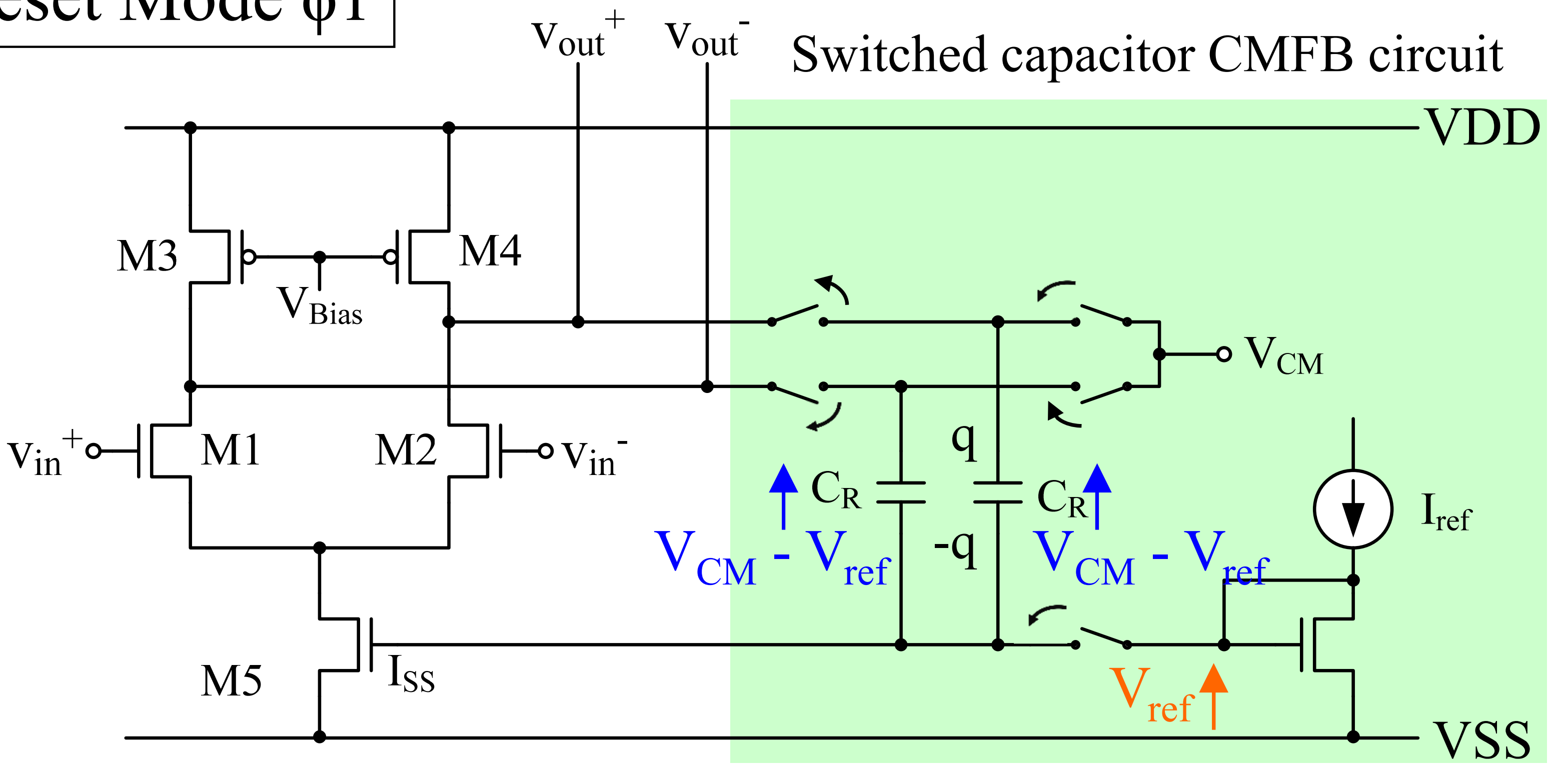
R.A.Whatley, U.S.Pat. 4, 573, 020, (1986)

Symmetrical implementation of continuous-time CMFB



Dynamic CMFB for discrete-time OPA (1)

Reset Mode ϕ1

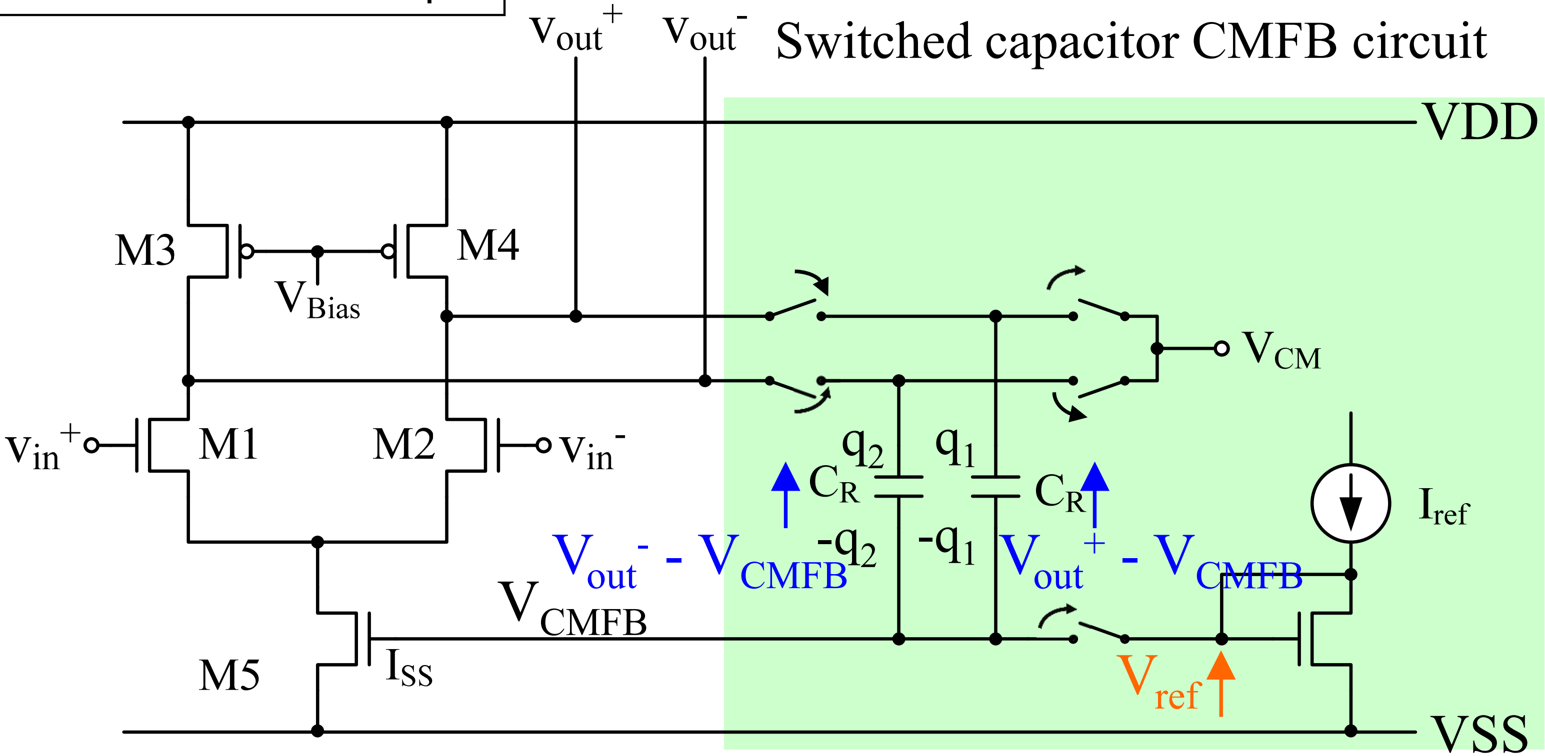


$$q = C_R(V_{CM} - V_{ref})$$

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

Dynamic CMFB for discrete-time OPA (2)

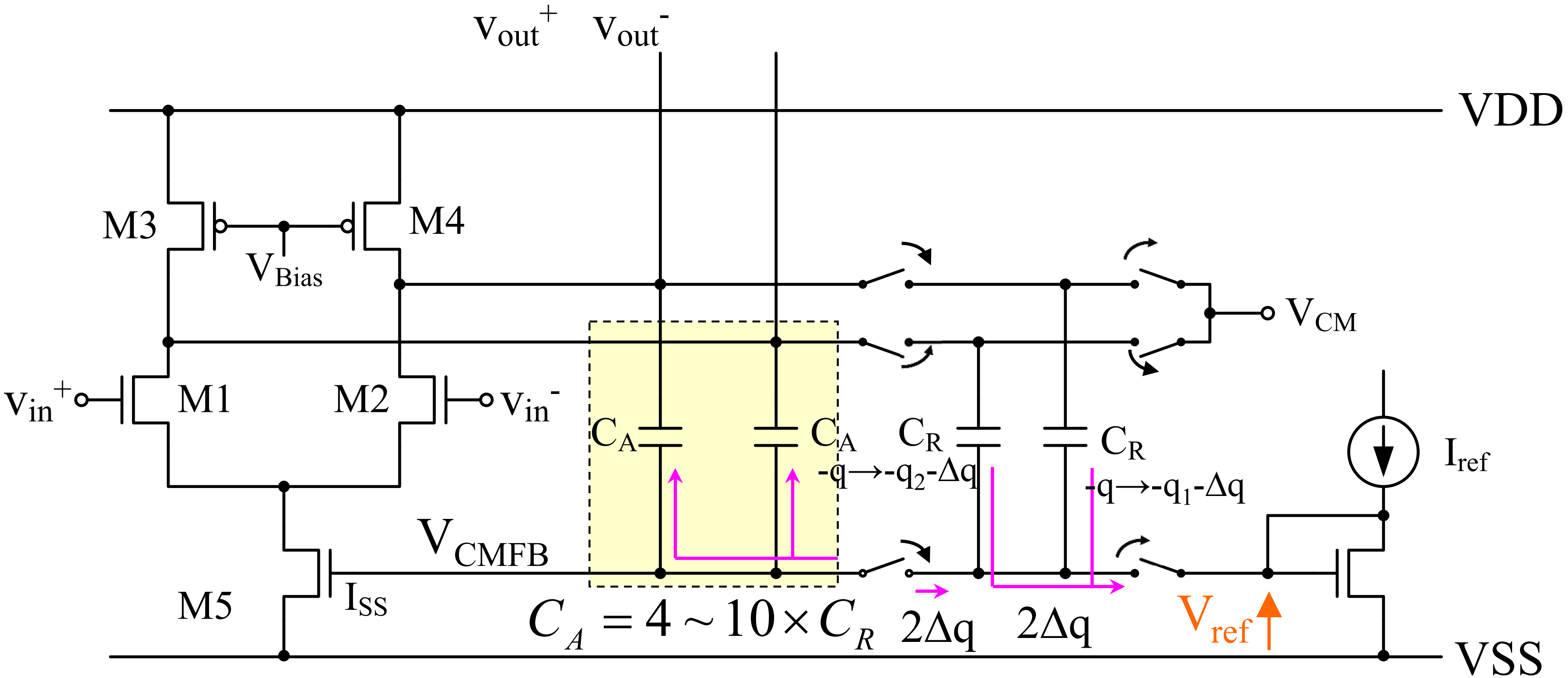
Amplification Mode ϕ2



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

If the common-mode output = V_{CM}, $I_{SS} = I_{ref}$ ← $V_{CMFB} = \frac{V_{out}^+ + V_{out}^-}{2} - V_{CM} + V_{ref}$

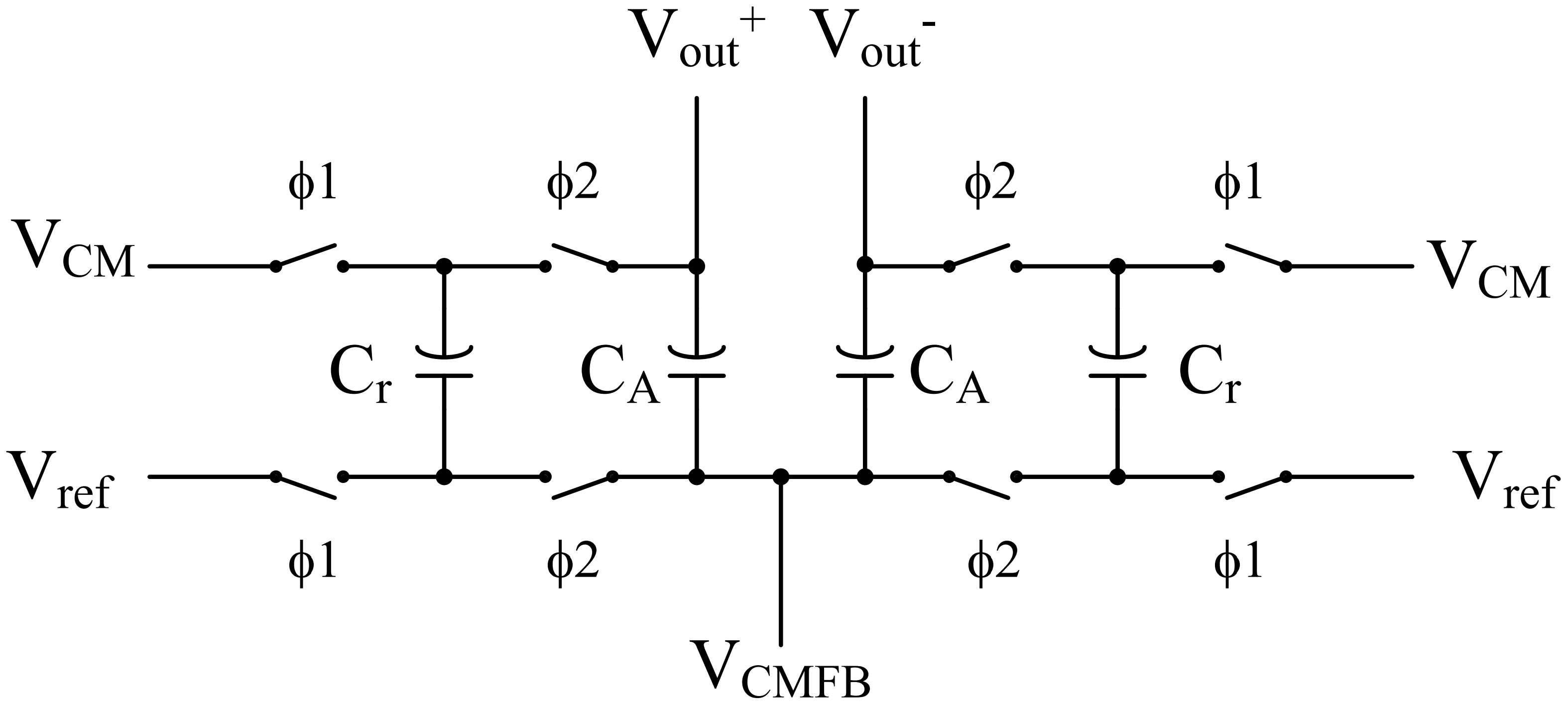
Cancellation of the parasitic capacitances in the CMOS switch



$$C_A = 4 \sim 10 \times C_R$$

Cancel of the charge
injection error of
CMOS switch

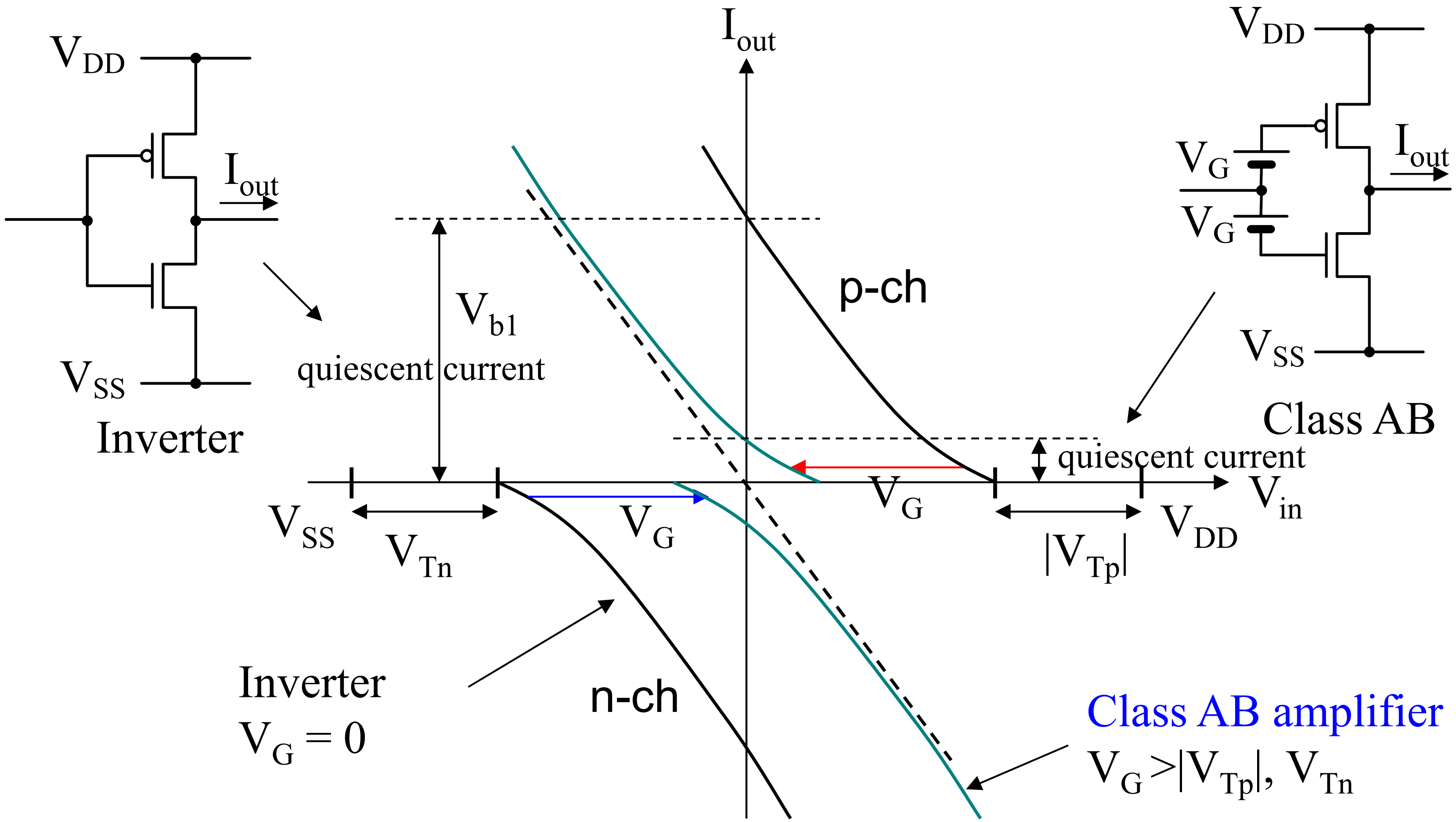
Symmetrical implementation of discrete-time CMFB



Symmetric schematic (intended for layout design)

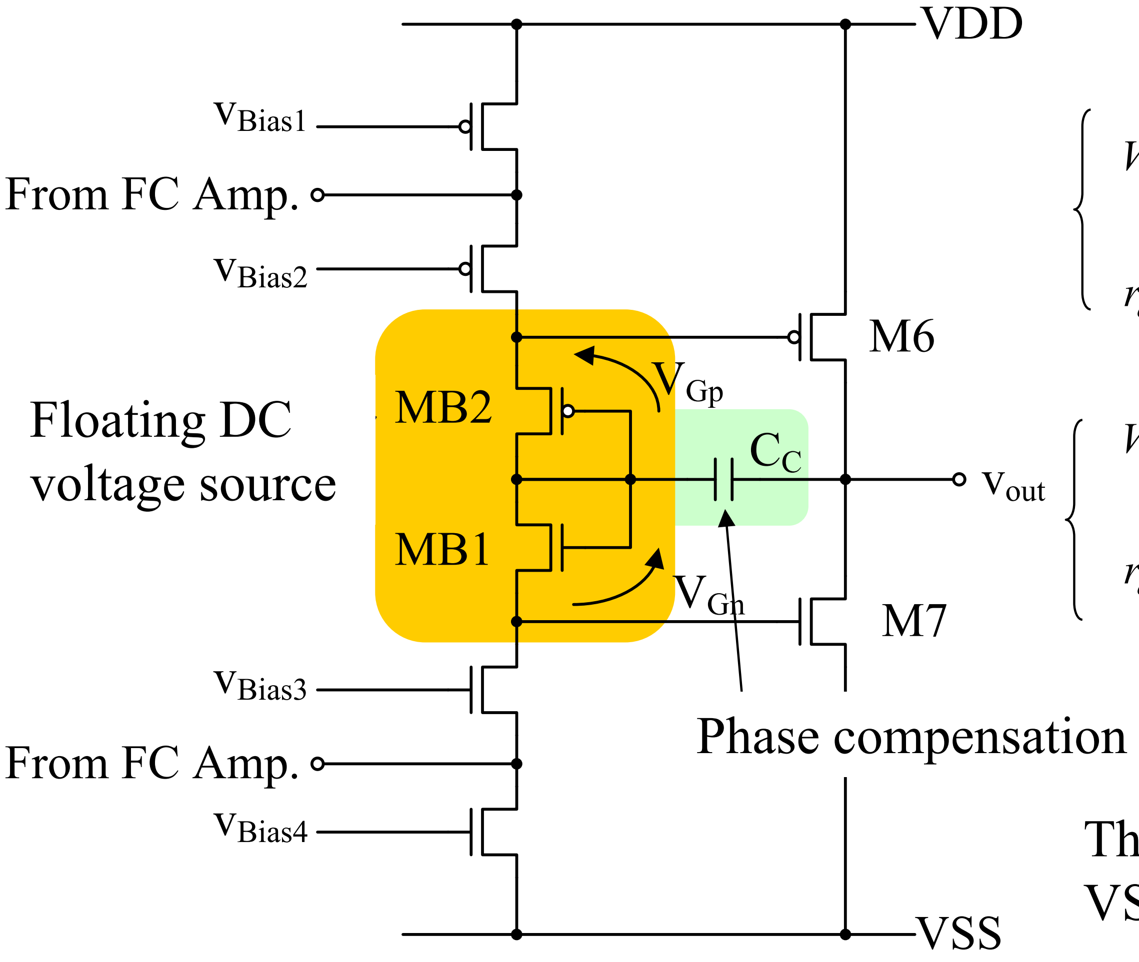
13.8 Output buffer for OPA

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

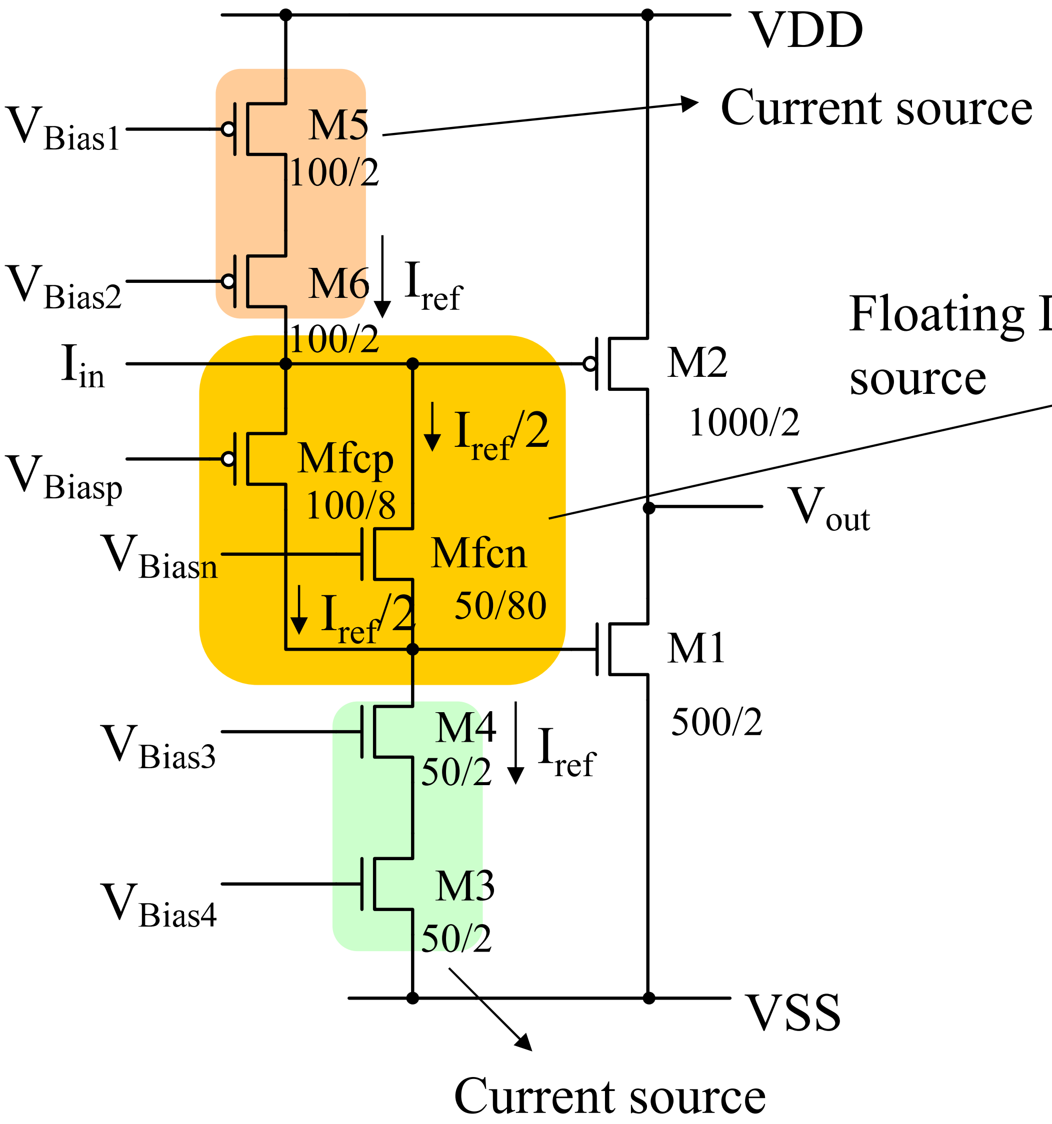


$$\begin{cases} V_{Gp} = |V_{Tp}| + \sqrt{\dfrac{2I_{DS\_MB2}}{\beta_p}} & \text{Floating DC voltage} \\ r_{ds\_MB2} \cong \dfrac{1}{g_{m\_MB2}} = 1/\sqrt{2\beta_p I_{DS}} \ge \dfrac{1}{g_{m6}} & \text{Zero cancel} \end{cases}$$

$$\begin{cases} V_{Gn} = V_{Tn} + \sqrt{\dfrac{2I_{DS\_MB1}}{\beta_n}} & \text{Floating DC voltage} \\ r_{ds\_MB1} \cong \dfrac{1}{g_{m\_MB1}} = 1/\sqrt{2\beta_n I_{DS}} \ge \dfrac{1}{g_{m7}} & \text{Zero cancel} \end{cases}$$

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

Common gate level shift

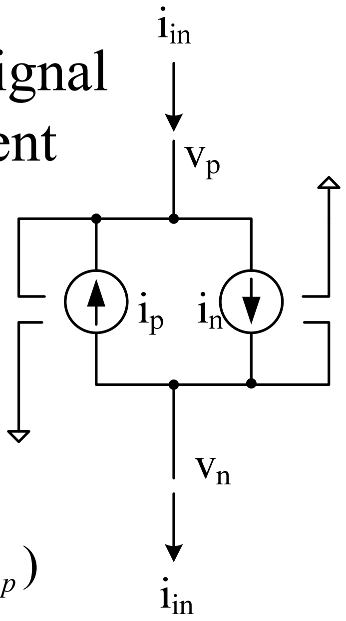


Current source

Floating DC current source

Current source

Small-signal equivalent circuit



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

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

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

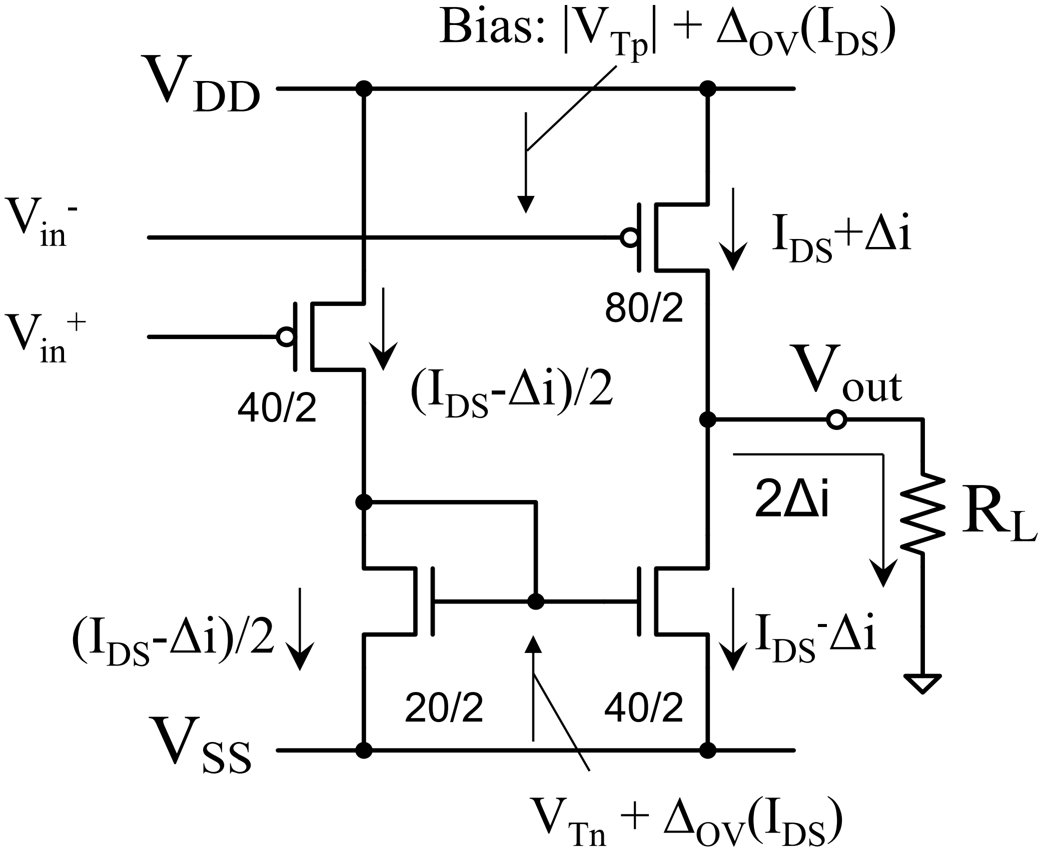
If $g_{mfcp} = g_{mfcn} \equiv g_{mfc}$,

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

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

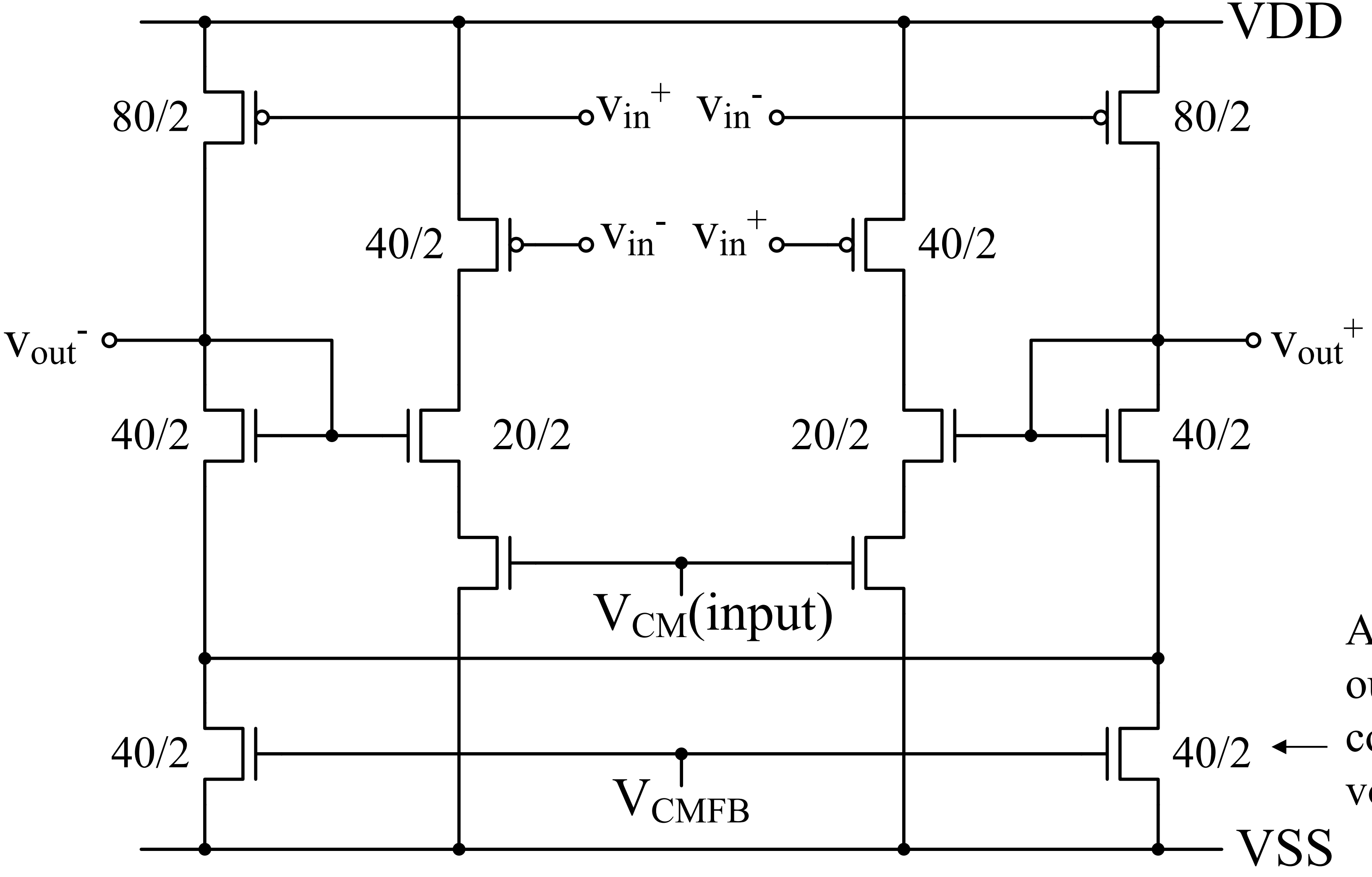
Class AB differential buffer for OPA

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



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

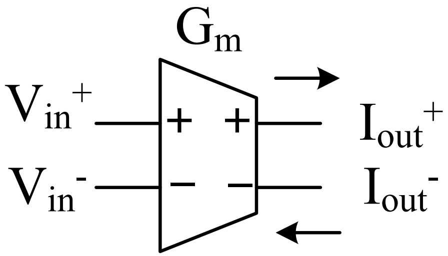
Practical class AB differential buffer



Adjusting the output common-mode voltage.

13.9 Operational transconductance amplifier (OTA)

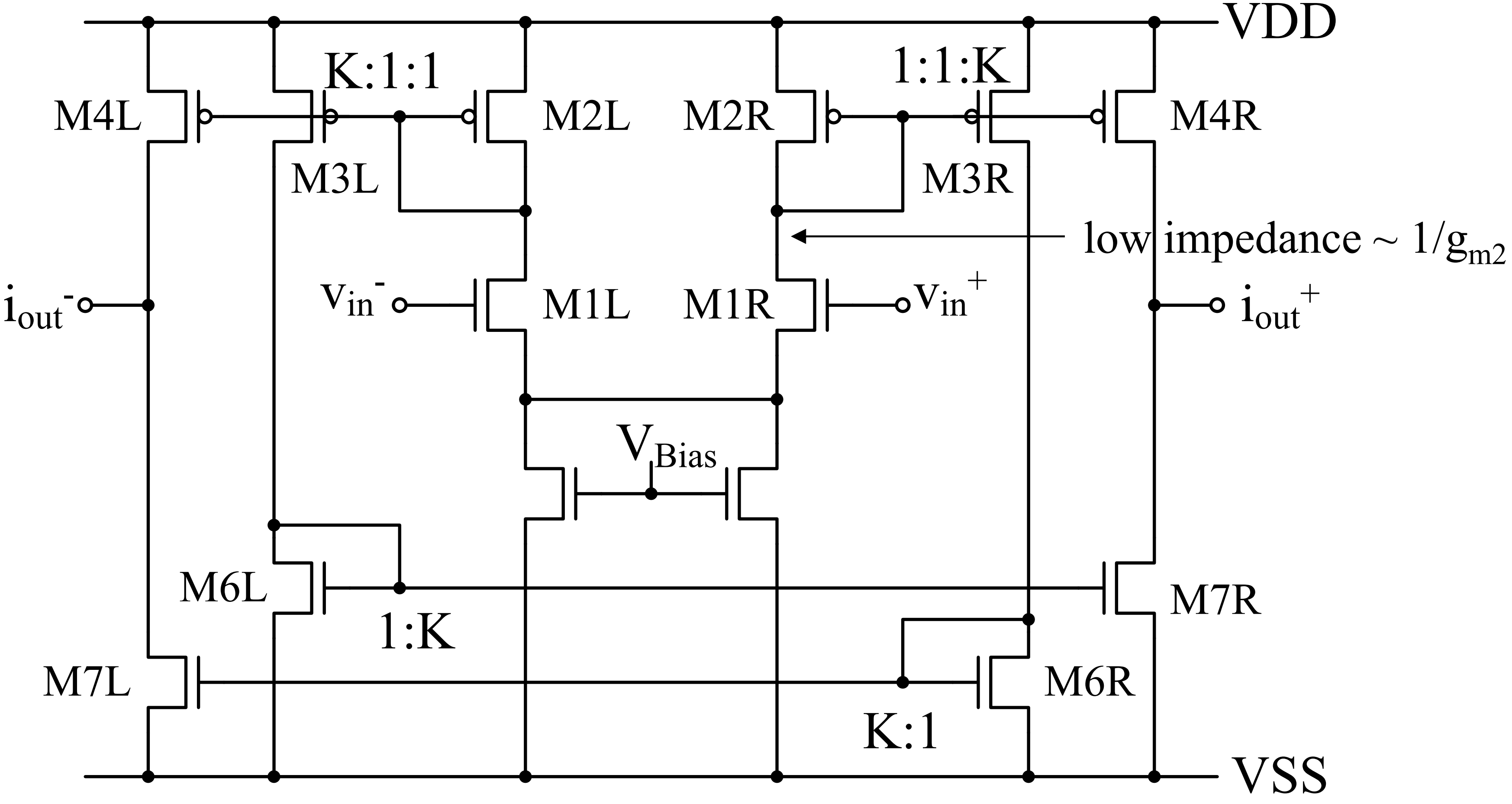
Functions of OTA



$$\begin{cases} I_{out}^{+} = G_m(V_{in}^{+} - V_{in-}) \\ I_{out}^{-} = -G_m(V_{in}^{+} - V_{in-}) \end{cases}$$

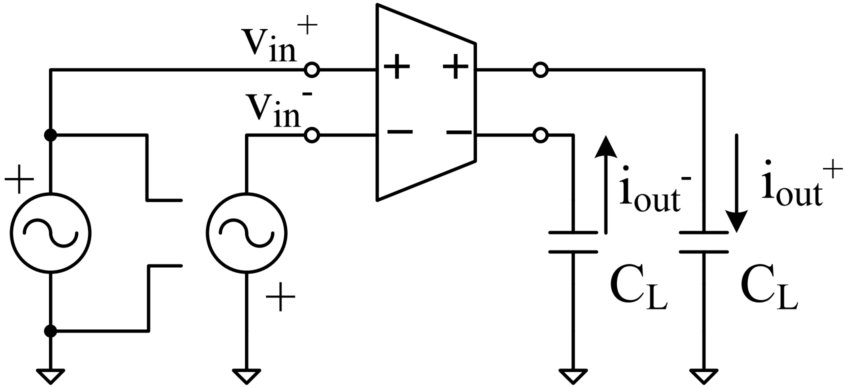
- Differential voltage input and differential current output
- All node are low impedance except the input and output nodes.
- Differences with OPA
  - High output resistance
    - OTA cannot drive the resistive load.
  - Unity gain frequency decreases with increasing C_L.
    - This characteristic is 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

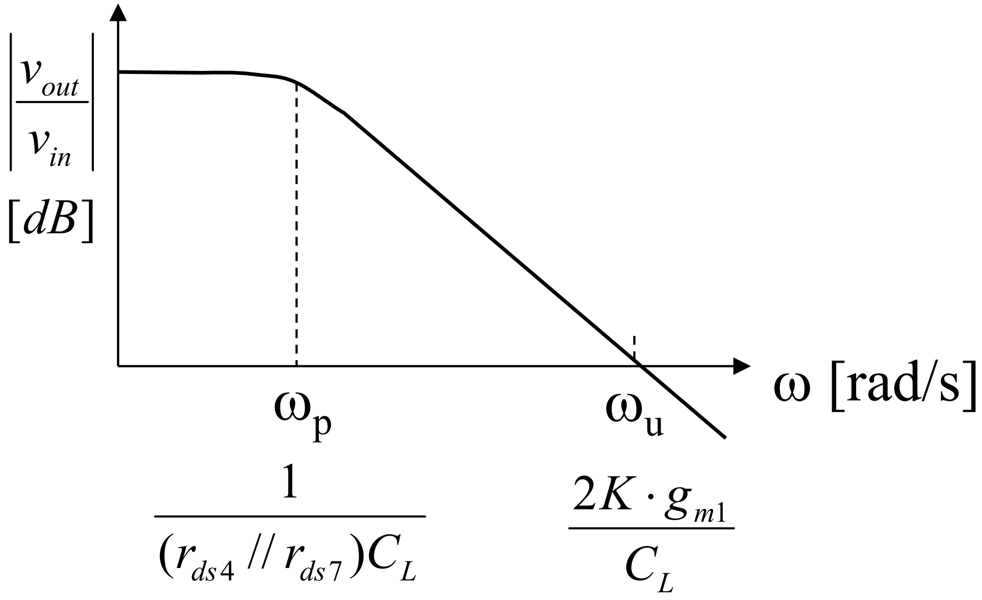


$$i_{out}^+ = K \cdot g_{m1}(v_{in}^+ - v_{in}^-) = G_m(v_{in}^+ - v_{in}^-)$$

Characteristics of gm-C filter



g_m-C integrator



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

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

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

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

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

(The maximum current of M4 is K･ISS.)

Cascode OTA