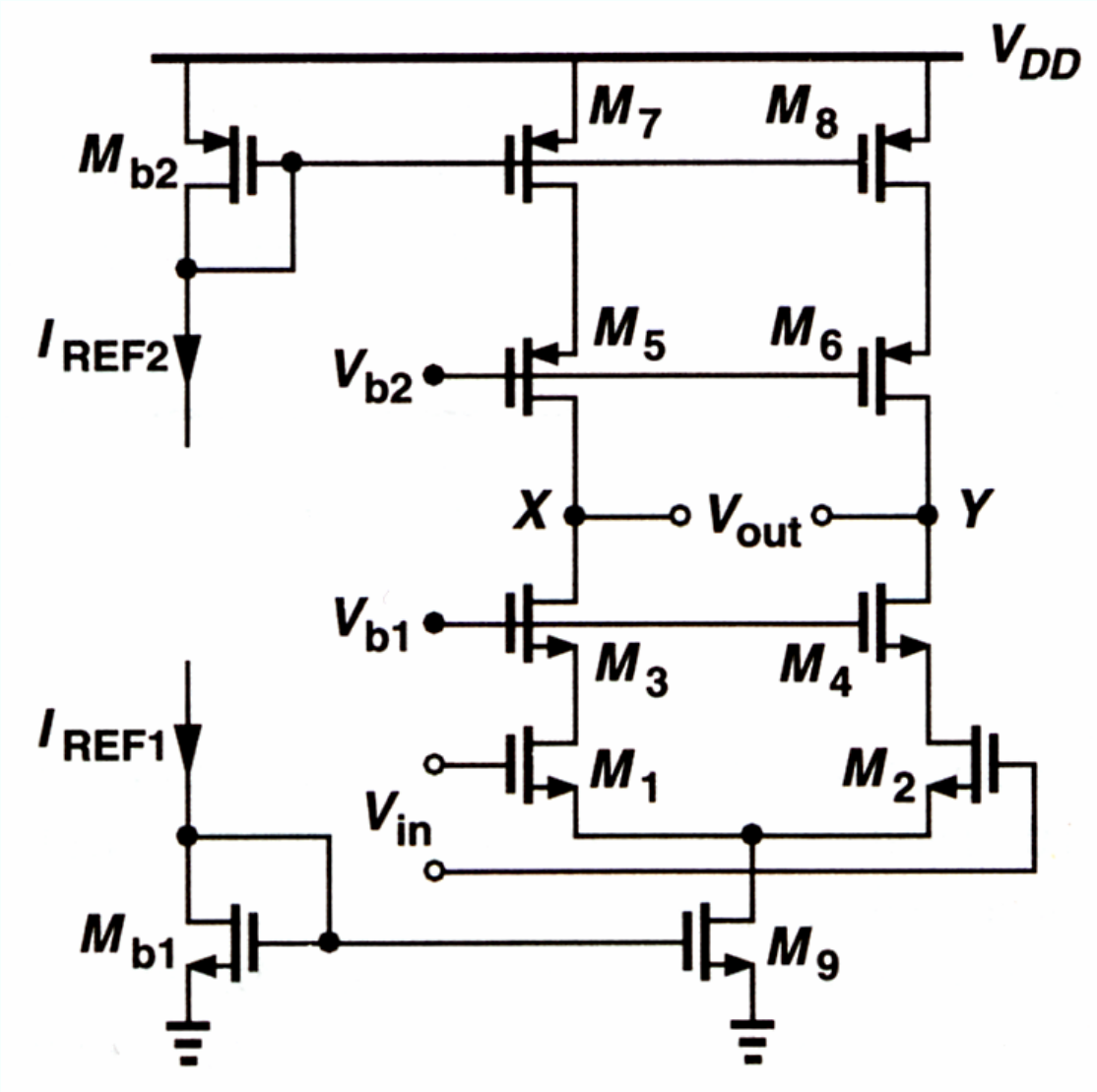
3. Folded Cascode OP amp

Telescopic OP amp



Telescopic OP amp:

(1) Large gain

(2) High speed

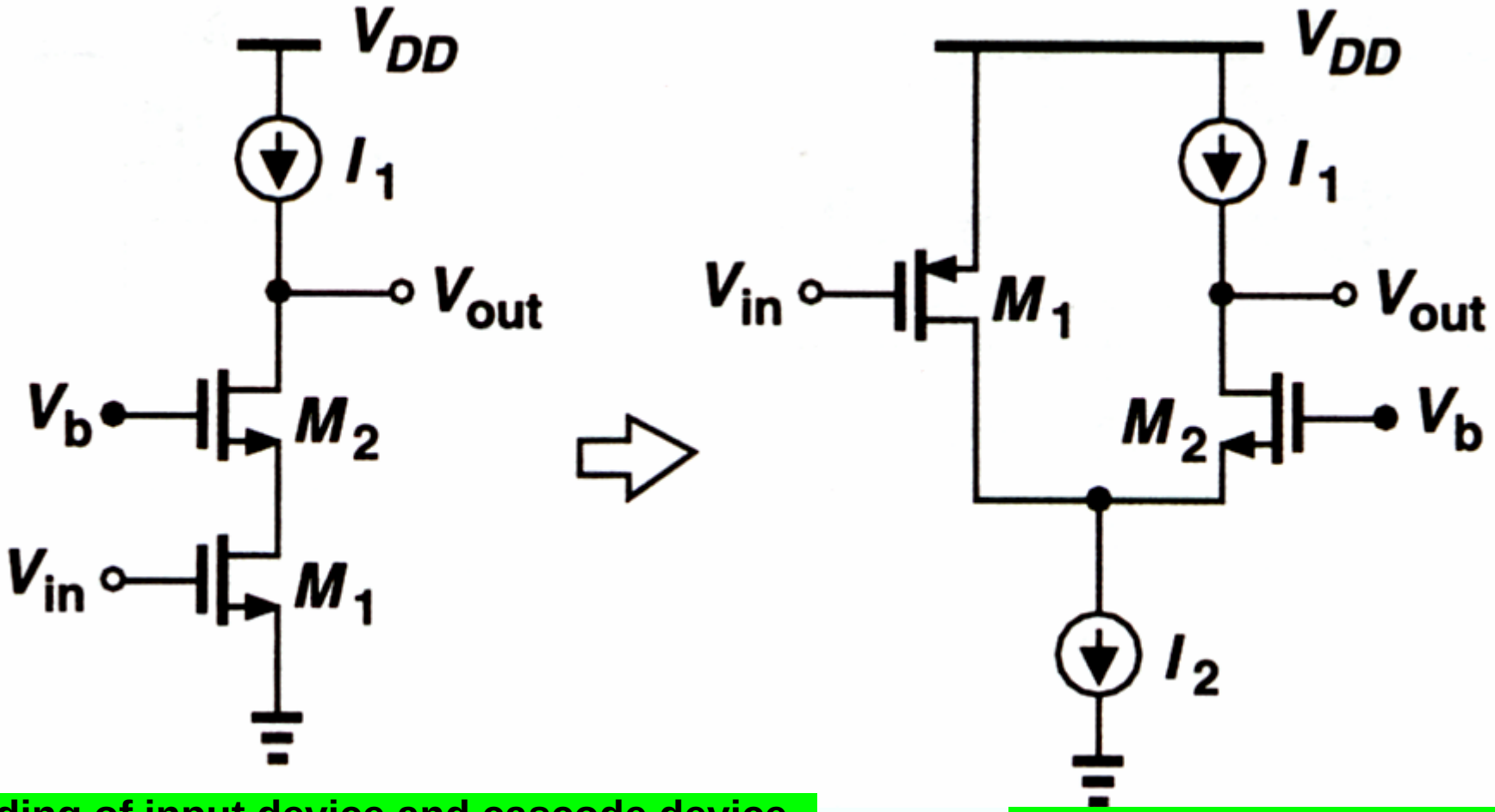
small parasitic cap➔high freq non-dominant pole

(3) Small ICMR

(4) Small OVR

(5) Not suitable for unity gain buffer

Conversion of cascode amp into folded cascode



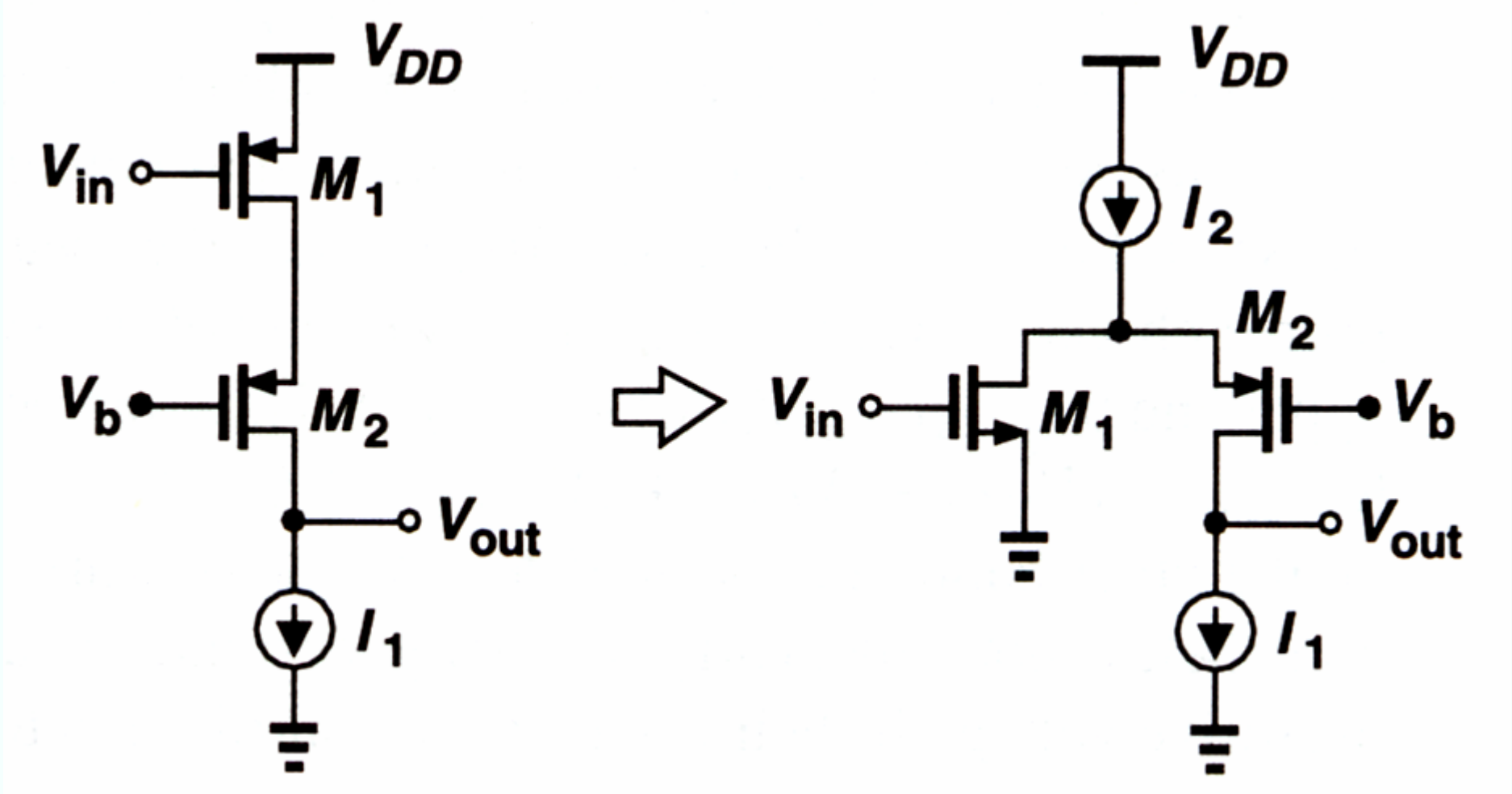
cascading of input device and cascode device

NO cascading of input device

Vb affects both max Vin and min Vout (max Vin=Vb-Vdsat, min Vout=Vb-Vth) Tradeoff between Vin and Vout ranges

Vb affects Vout range only (min Vin: Vdsat-Vth, min Vout=Vb-Vth=2 Vdsat), no tradeoff

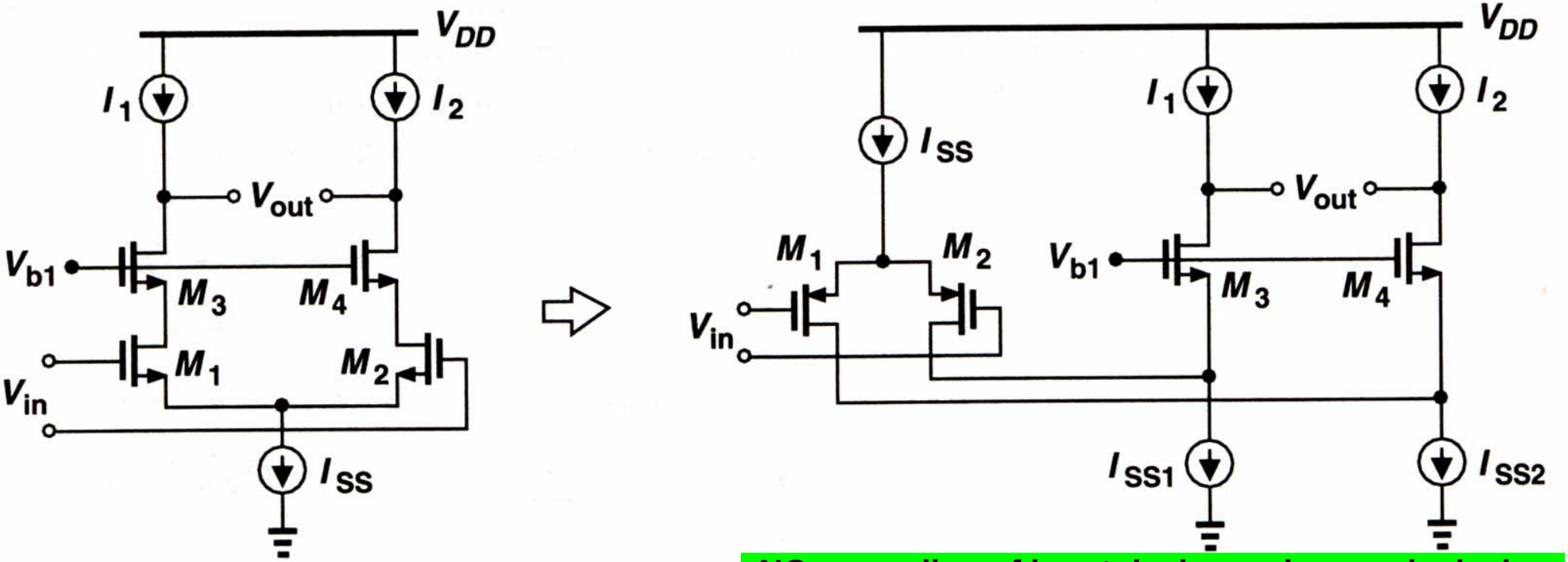
Conversion of cascode amp into folded cascode



Av = gm1 x Rout

(about the same in both cases)

Conversion of Diff cascode amp into Diff folded cascode



NO cascading of input device and cascode device

Vb1 affects both max Vin and min Vout (max Vin=Vb-Vdsat, min Vout=Vb-Vth) Tradeoff between Vin and Vout ranges

Vb1 affects Vout range only (min Vin: Vdsat-Vth, min Vout=Vb-Vth=2 Vdsat), no tradeoff

Av = gm1 x Rout (about the same in both cases)

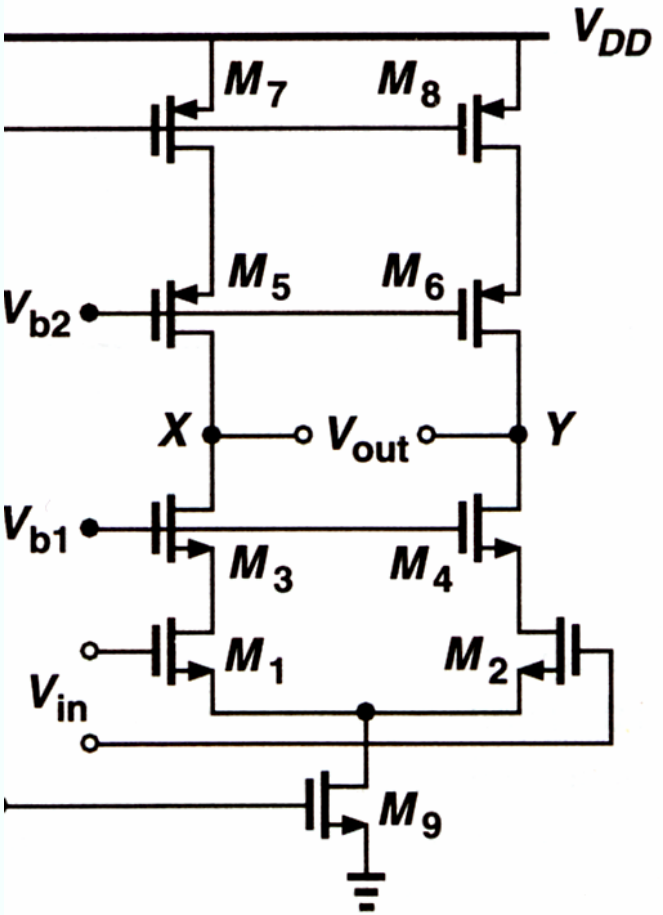
Rout (left) = gm3 ro3 ro1 , Rout (right) = gm3 ro3 (ro2 || ross1)

Folded cascode OP amp

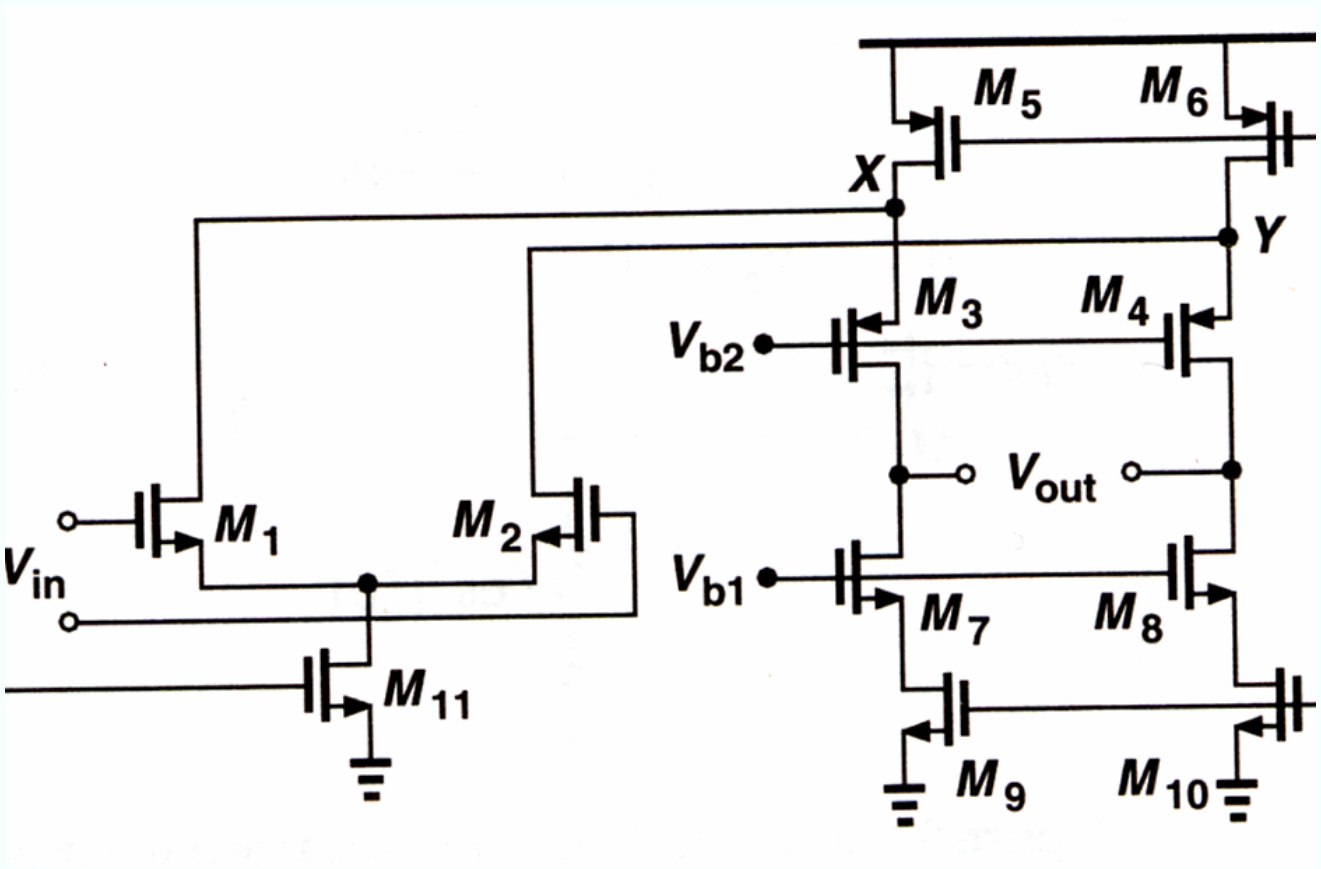
Telescopic OP amp의 단점:

(1) limited output swing, limited input CM range

(2) limited swing in unity-gain feedback configuration

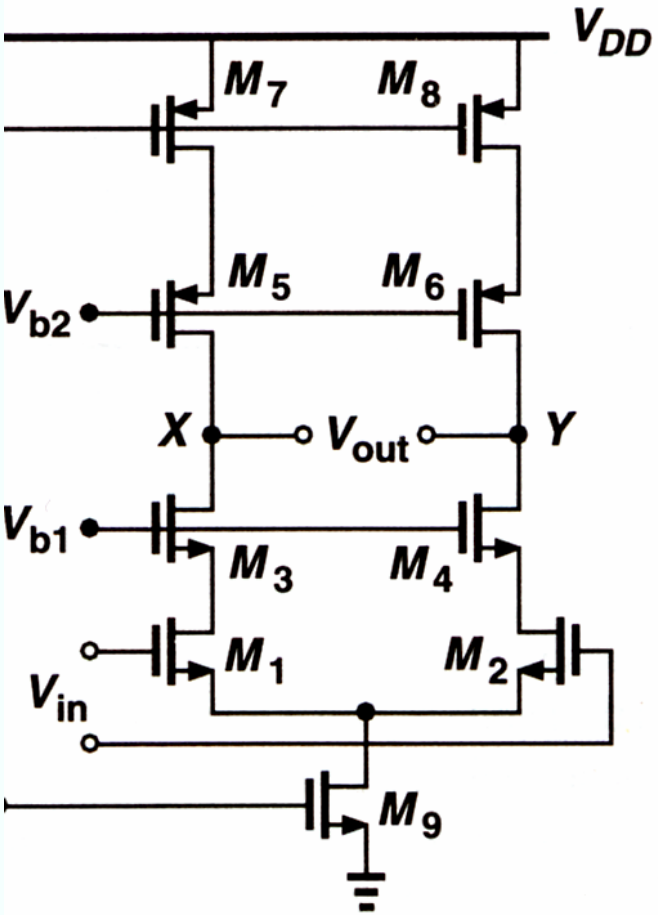


Telescopic

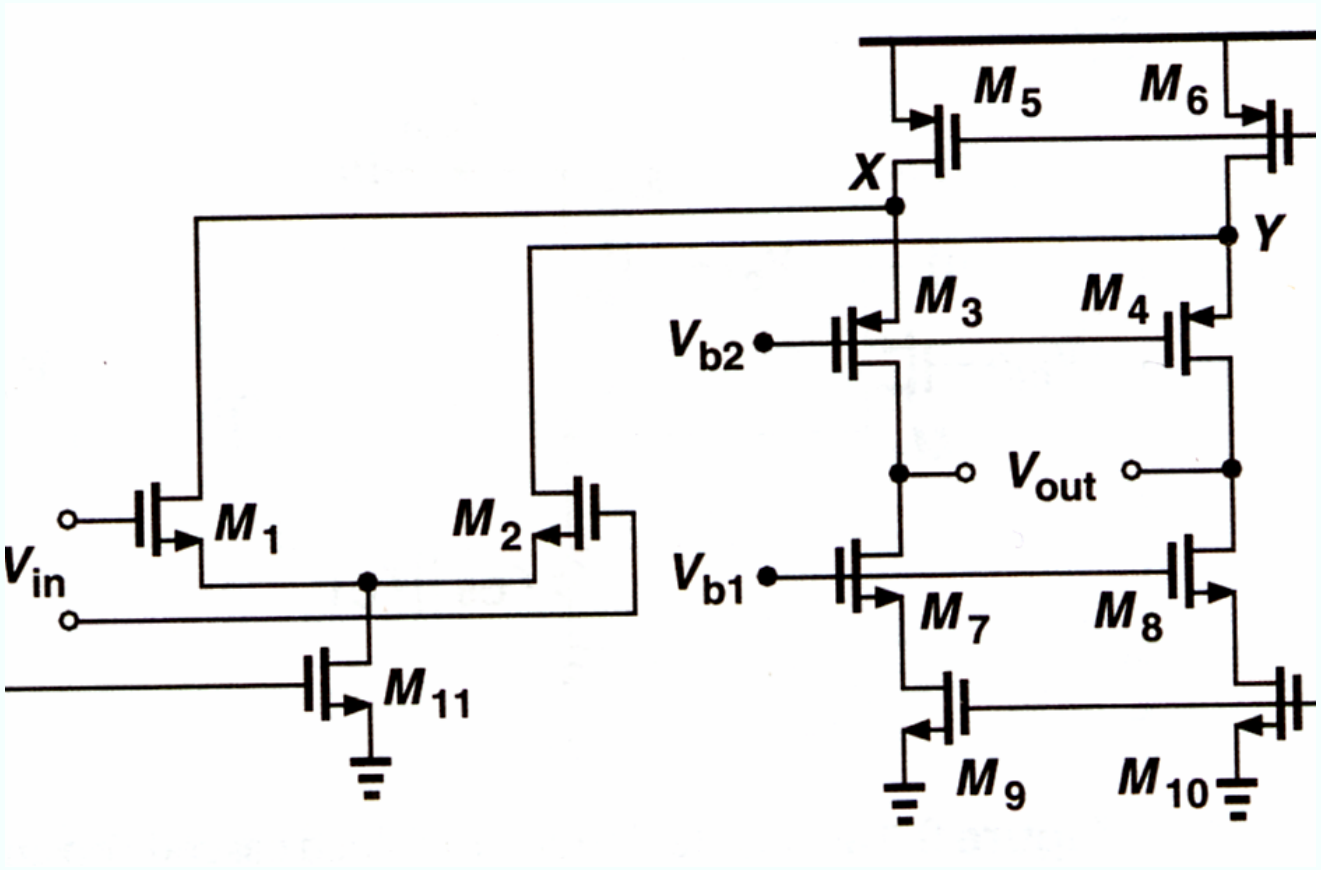


Folded cascode

Folded cascode OP amp



Telescopic



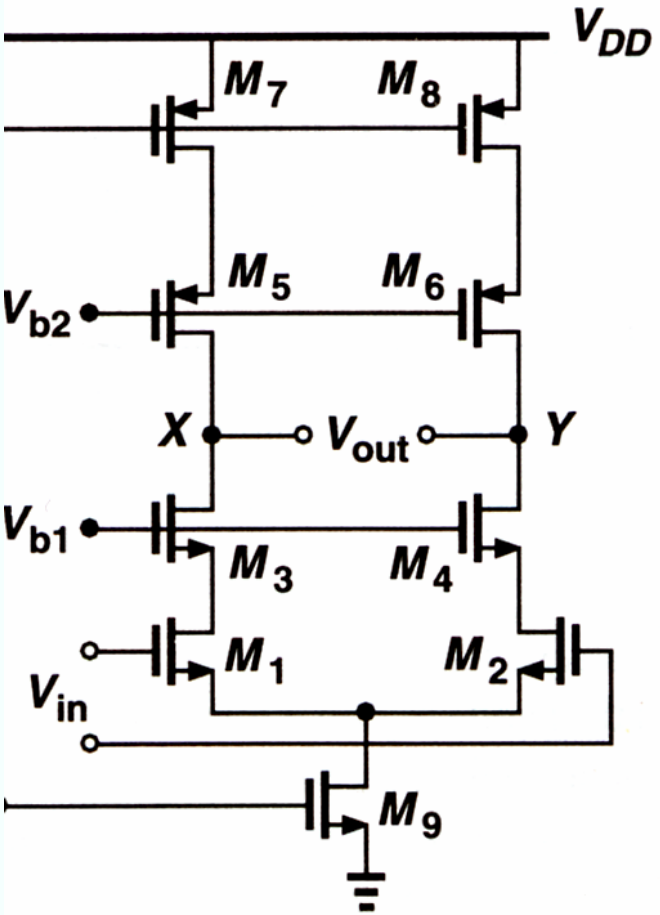
Folded cascode

Input Common mode voltage range

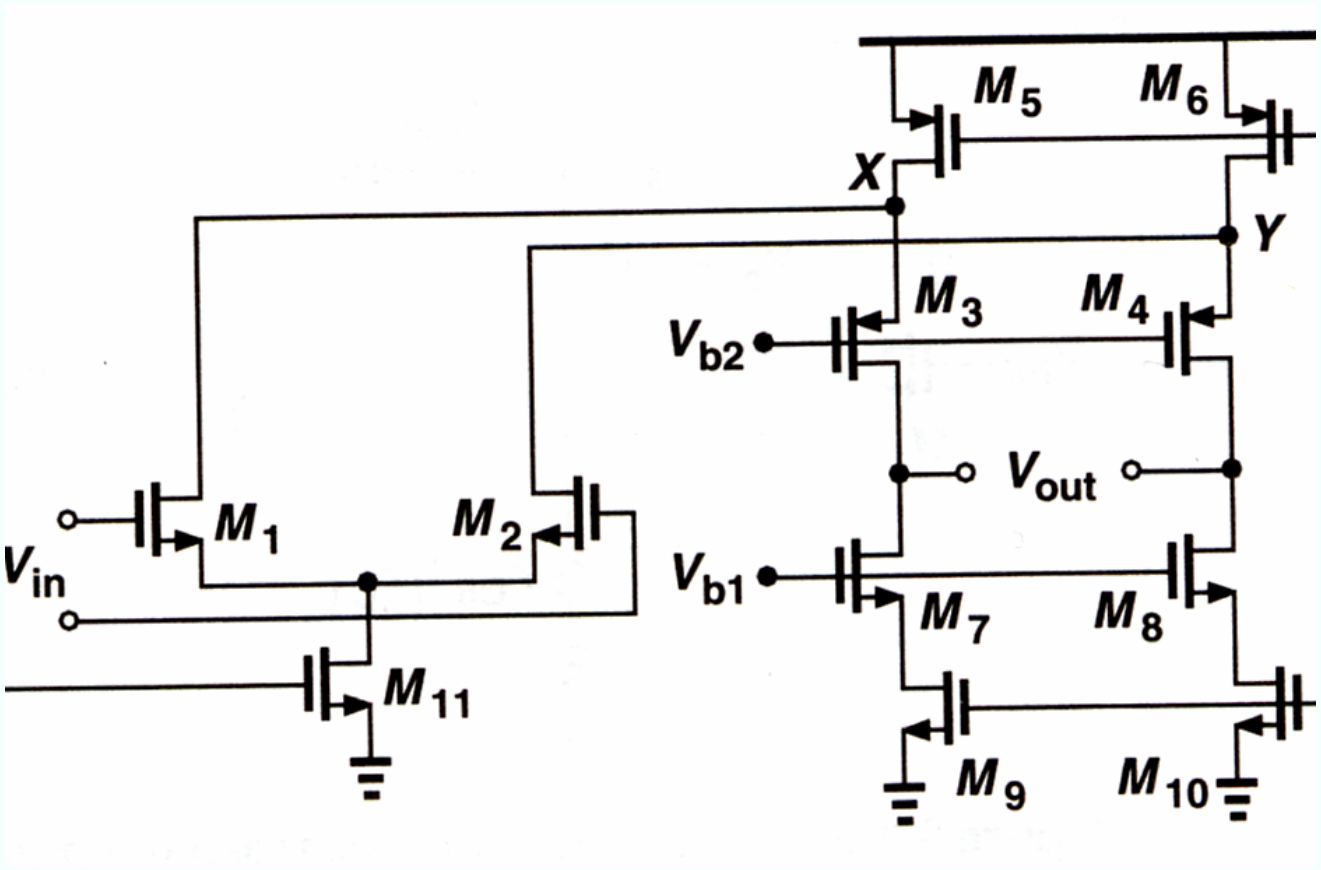
(1) Telescopic: 2 VDSAT + VTH, Vb1 - VDSAT (2 VDSAT+VTH)

(2) Folded cascode: 2 VDSAT + VTH, VG56+VTH (VDD-VDSAT)

Folded cascode OP amp



Telescopic



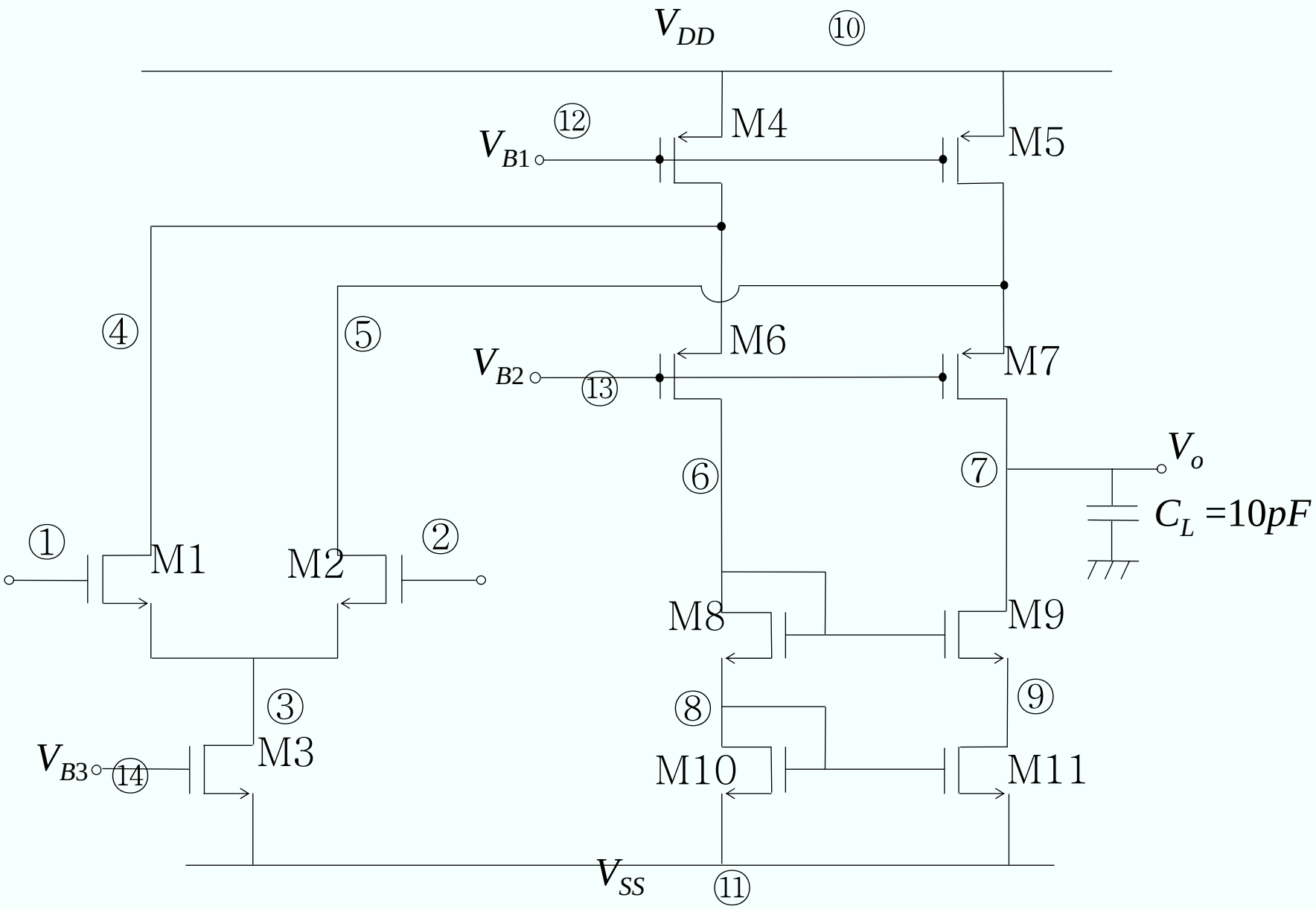
Folded cascode

Output voltage range

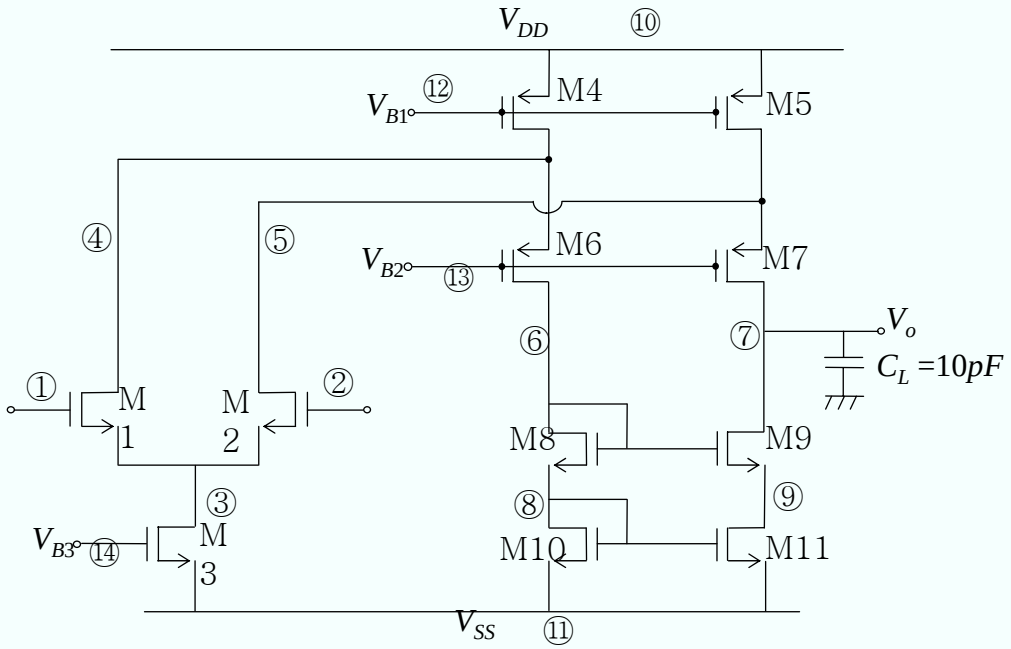
(1) Telescopic: Vb1-Vth, Vb2+Vth (3 Vdsat+Vth, VDD-2 Vdsat)

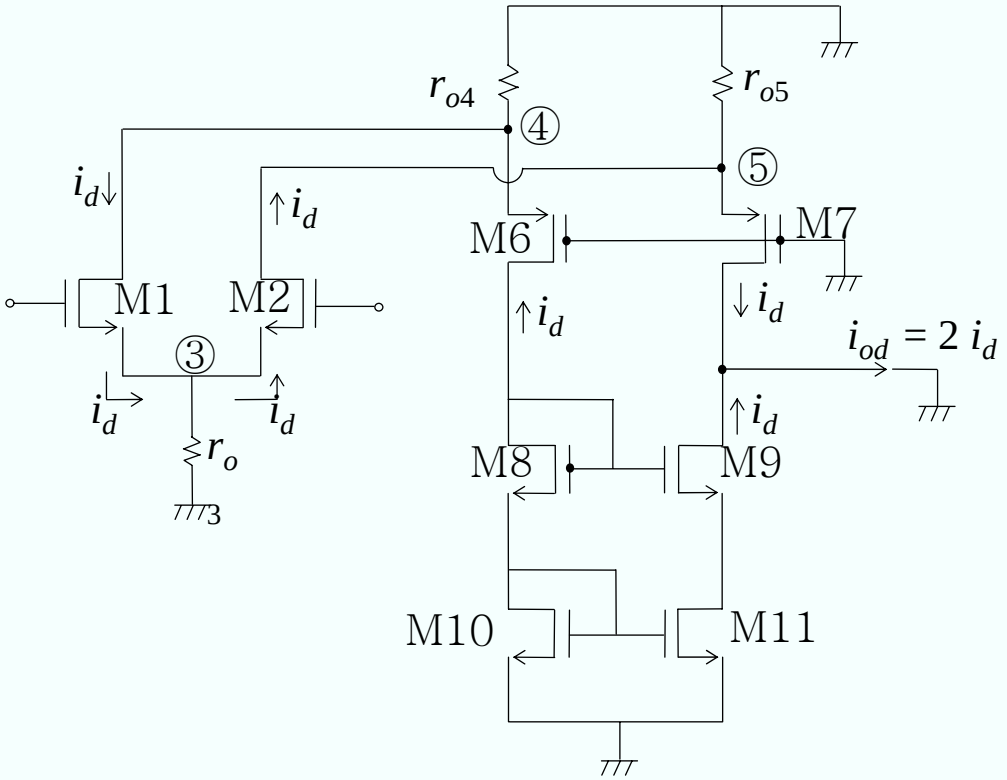
(2) Folded cascode: Vb1-Vth, Vb2+Vth (2 Vdsat, VDD-2 Vdsat)

Single-ended folded cascode OP amp



Single-ended folded cascode OP amp



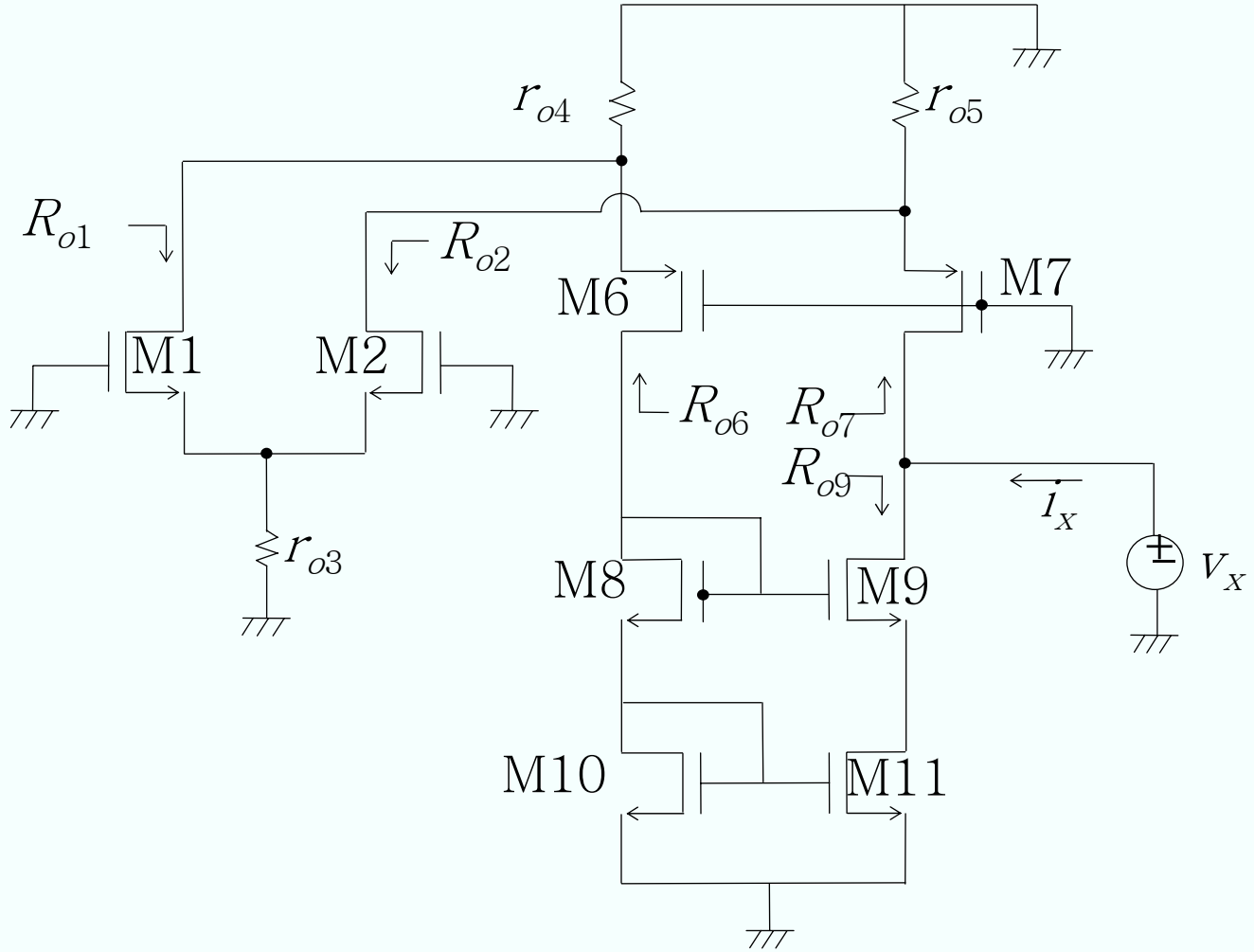


Small-signal analysis

$$i_d = \frac{v_{id}}{r_{s1} + r_{s2}} = \frac{1}{2} g_{m1} v_{id}$$

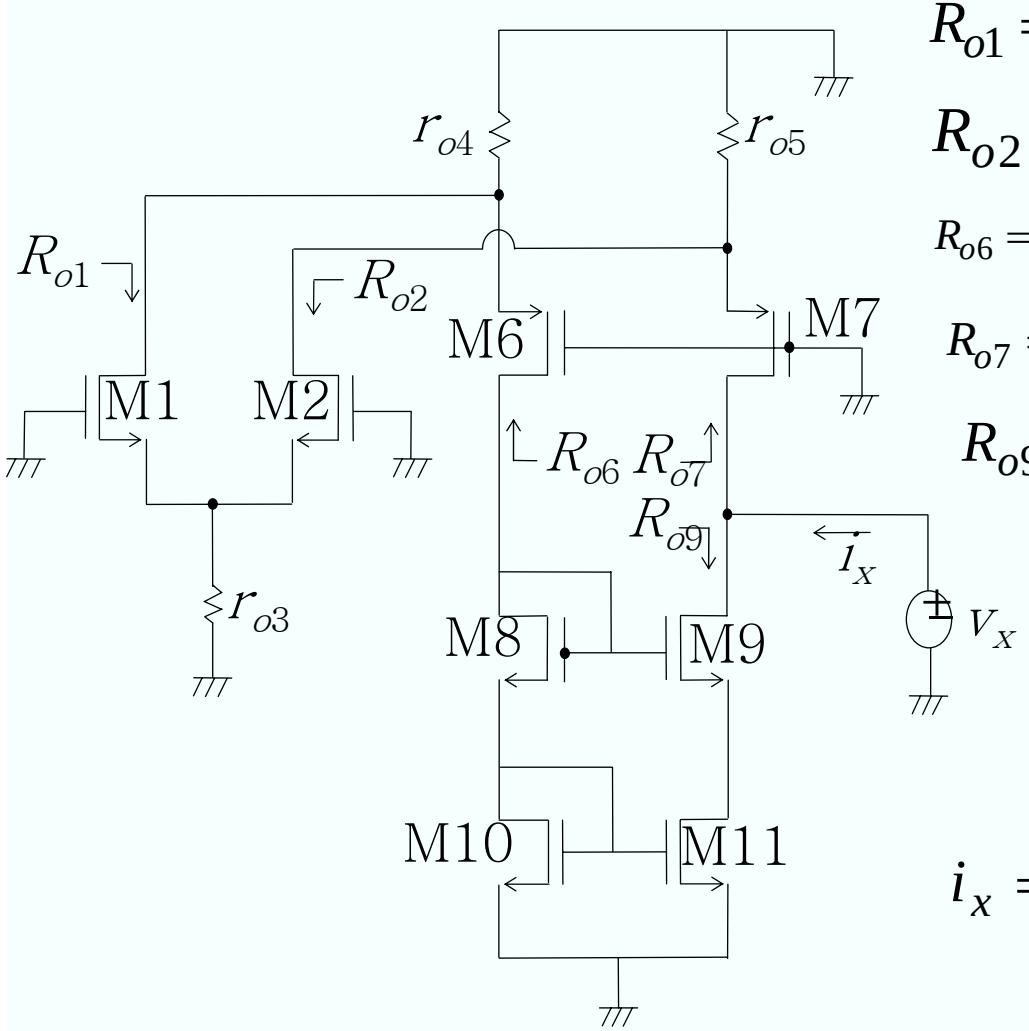
$$G_{md} = \frac{i_{od}}{v_{id}} = \frac{2i_d}{v_{id}} = g_{m1}$$

Single-ended folded cascode OP amp



$$R_o = \frac{v_x}{i_x} = \left\{ g_{m7} r_{o7} \cdot (r_{o2} \| r_{o5}) \right\} \| \left\{ g_{m9} r_{o9} \cdot r_{o11} \right\}$$

Single-ended folded cascode OP amp



$$R_{o1} = g_{m1}r_{o1} \cdot (r_{s2} \| r_{o3}) + r_{o1} + (r_{s2} \| r_{o3}) \approx 2r_{o1}$$

$$R_{o2} = 2r_{o2}$$

$$R_{o6} = g_{m6}r_{o6} \cdot (R_{o1} \| r_{o4}) + r_{o6} + (R_{o1} \| r_{o4}) \approx g_{m6}r_{o6} \cdot (R_{o1} \| r_{o4})$$

$$R_{o7} = g_{m7}r_{o7} \cdot ((2r_{o2}) \| r_{o5}) = R_{o6}$$

$$R_{o9} = g_{m9}r_{o9} \cdot r_{o11} + r_{o9} + r_{o11} \approx g_{m9}r_{o9} \cdot r_{o11}$$

$$i_x = i_{x7} + i_{x9} \qquad i_{x9} = \frac{v_x}{R_{o9}}$$

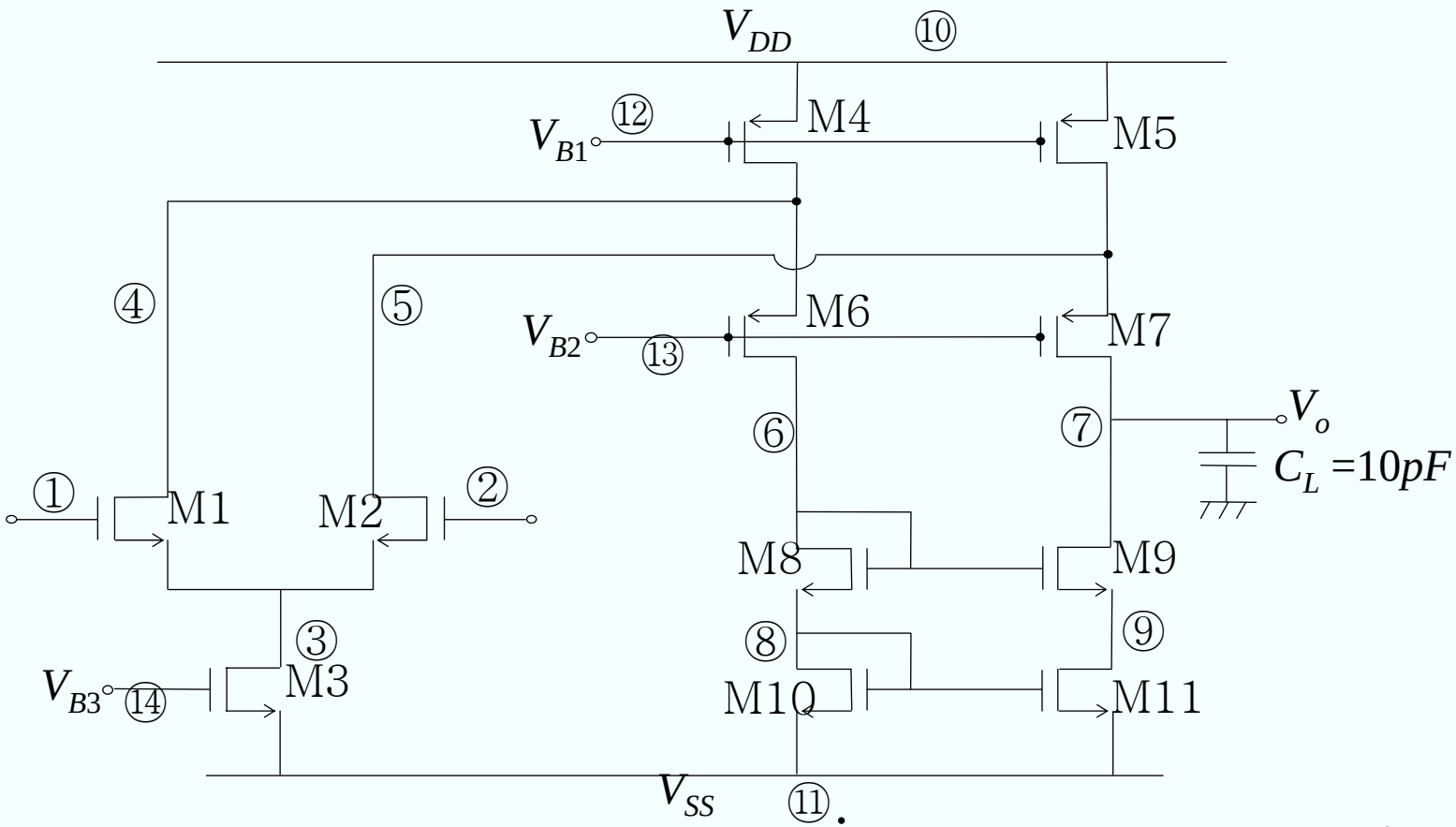
$$i_{x7} = \frac{v_x}{R_{o7}} \cdot \left(1 + \frac{r_{o5}}{r_{o5} + R_{o2}}\right) \approx \frac{v_x}{(g_{m7}r_{o7}) \cdot (r_{o2} \| r_{o5})}$$

$$i_x = i_{x7} + i_{x9} = \frac{v_x}{(g_{m7}r_{o7}) \cdot (r_{o2} \| r_{o5})} + \frac{v_x}{g_{m9}r_{o9} \cdot r_{o11}}$$

$$= \frac{v_x}{\{g_{m7}r_{o7} \cdot (r_{o2} \| r_{o5})\} \| \{g_{m9}r_{o9} \cdot r_{o11}\}}$$

$$R_o = \frac{v_x}{i_x} = \{g_{m7}r_{o7} \cdot (r_{o2} \| r_{o5})\} \| \{g_{m9}r_{o9} \cdot r_{o11}\}$$

Single-ended folded cascode OP amp

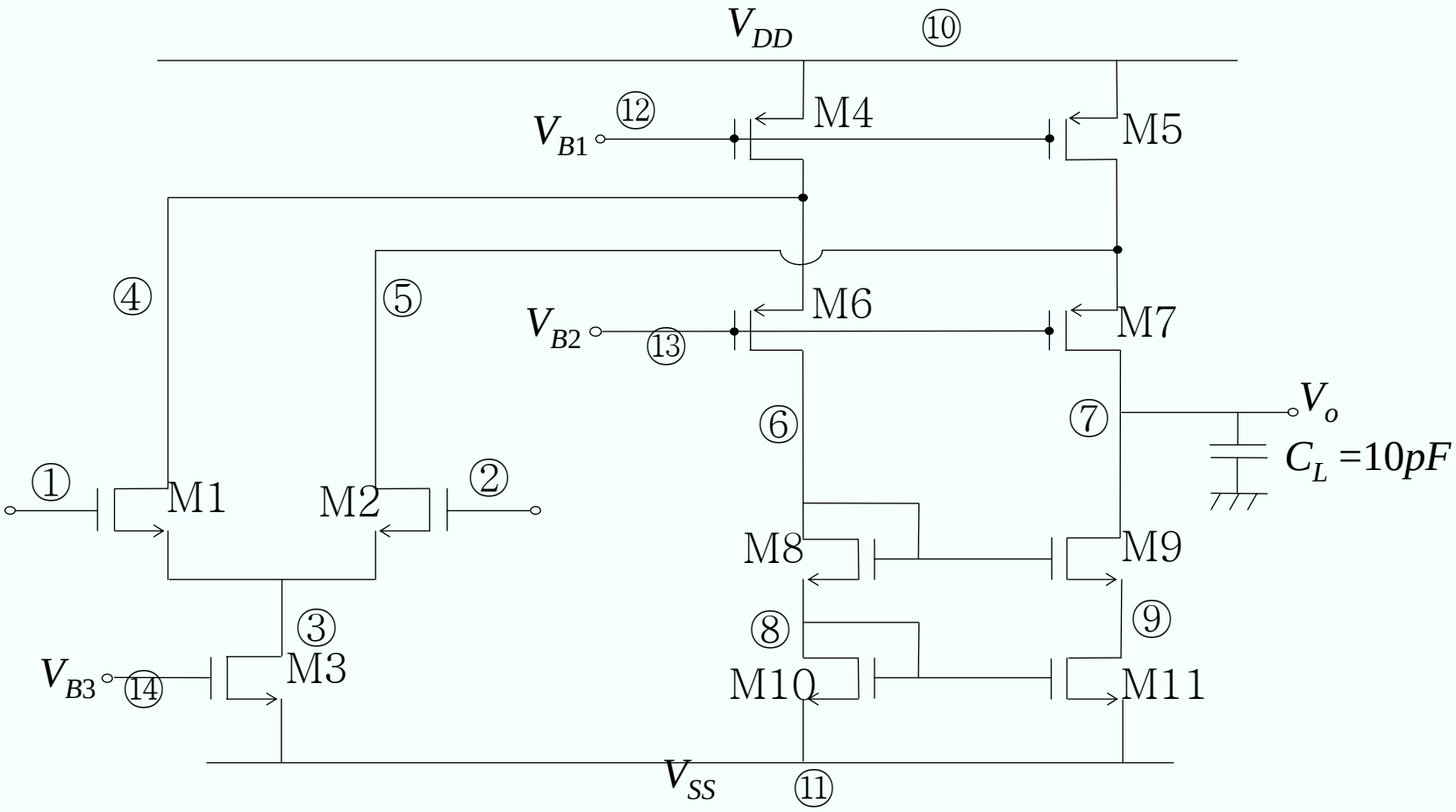


$$G_{mc} \triangleq \frac{i_{oc}}{v_{ic}} = -\frac{r_{s8} + r_{s10}}{(g_{m6}r_{o6}) \cdot (r_{o1} \| r_{o4}) \cdot 2r_{o3}}$$

No mismatch

$$CMRR \triangleq \left|\frac{A_{vd}}{A_{vc}}\right| = 2g_{m1}r_{o3} \cdot g_{m6}r_{o6} \cdot \frac{(r_{o1} \| r_{o4})}{(r_{s8} + r_{s10})}$$

Single-ended folded cascode OP amp

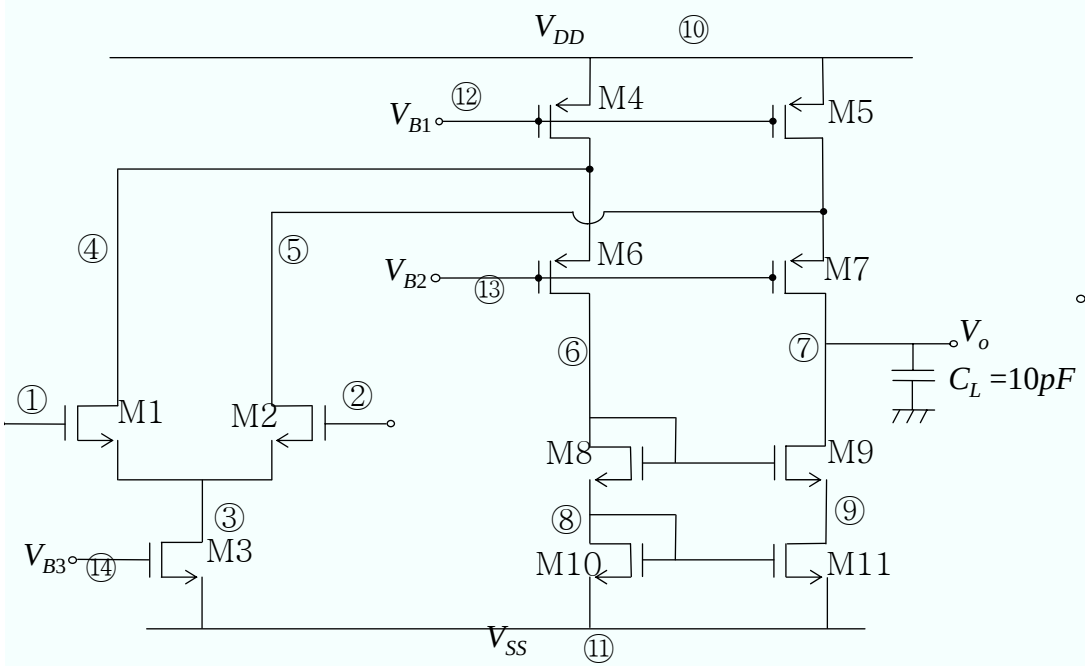


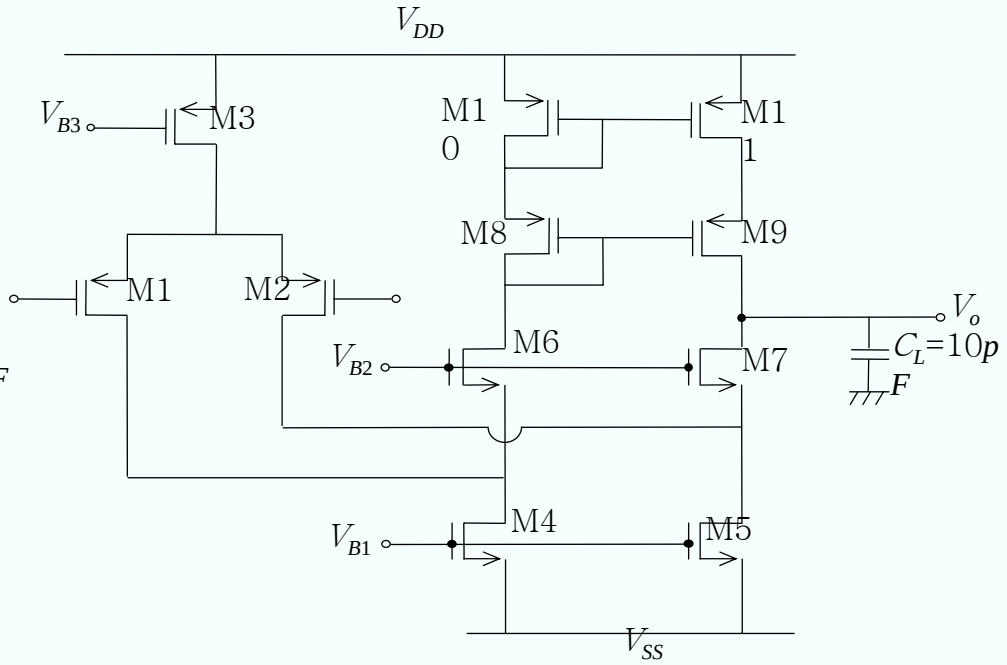
Active input common mode voltage range

$$V_{SS} + V_{DSAT\,3} + V_{GS\,1} = V_{SS} + V_{DSAT\,3} + V_{DSAT\,1} + V_{THn1}$$

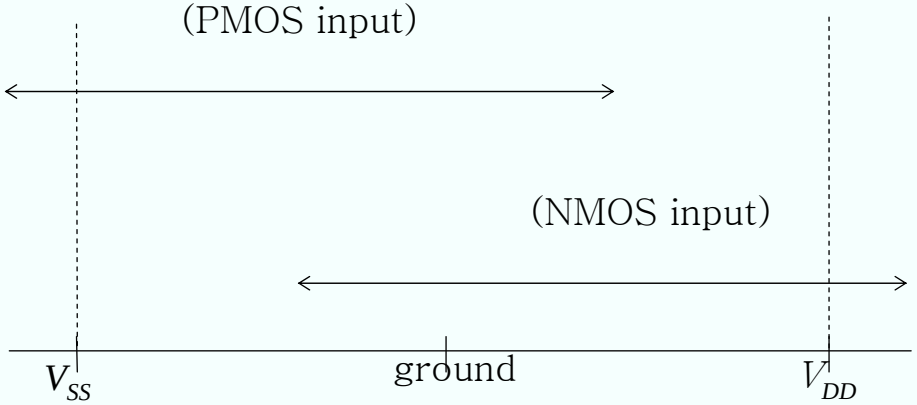
$$V_{DD} - \left|V_{DSAT\,4}\right| + V_{THn1}$$

Single-ended folded cascode OP amp

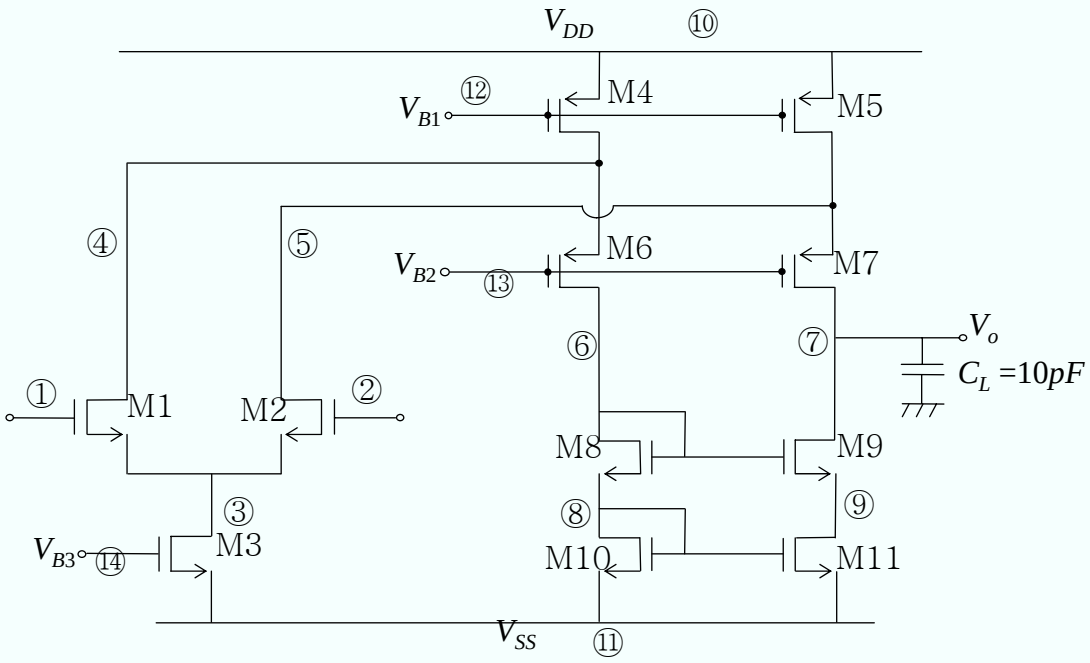


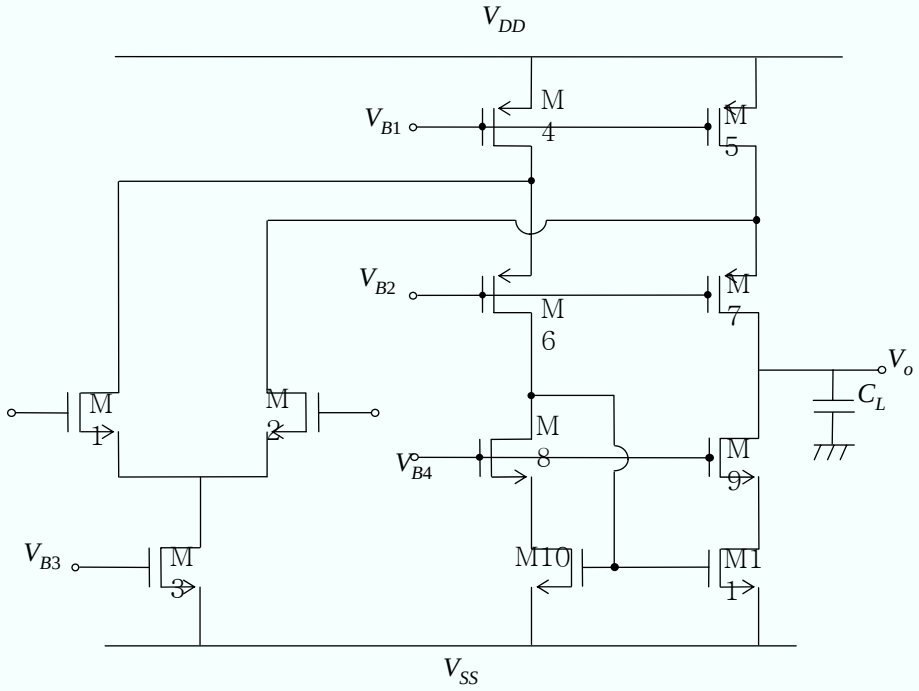


Active input common mode voltage range



Single-ended folded cascode OP amp





Output Voltage range (min, max)

$$= V_{SS} + V_{DSAT\ 11} + V_{DSAT\ 9} + V_{THn\ 11}$$

$$= V_{SS} + V_{DSAT\ 11} + V_{DSAT\ 9}$$

$$V_{B2} + \left|V_{THp\ 7}\right|$$

$$V_{B2} + \left|V_{THp\ 7}\right|$$

Fully diff folded cascode OP amp

Rail-to-rail input CM range

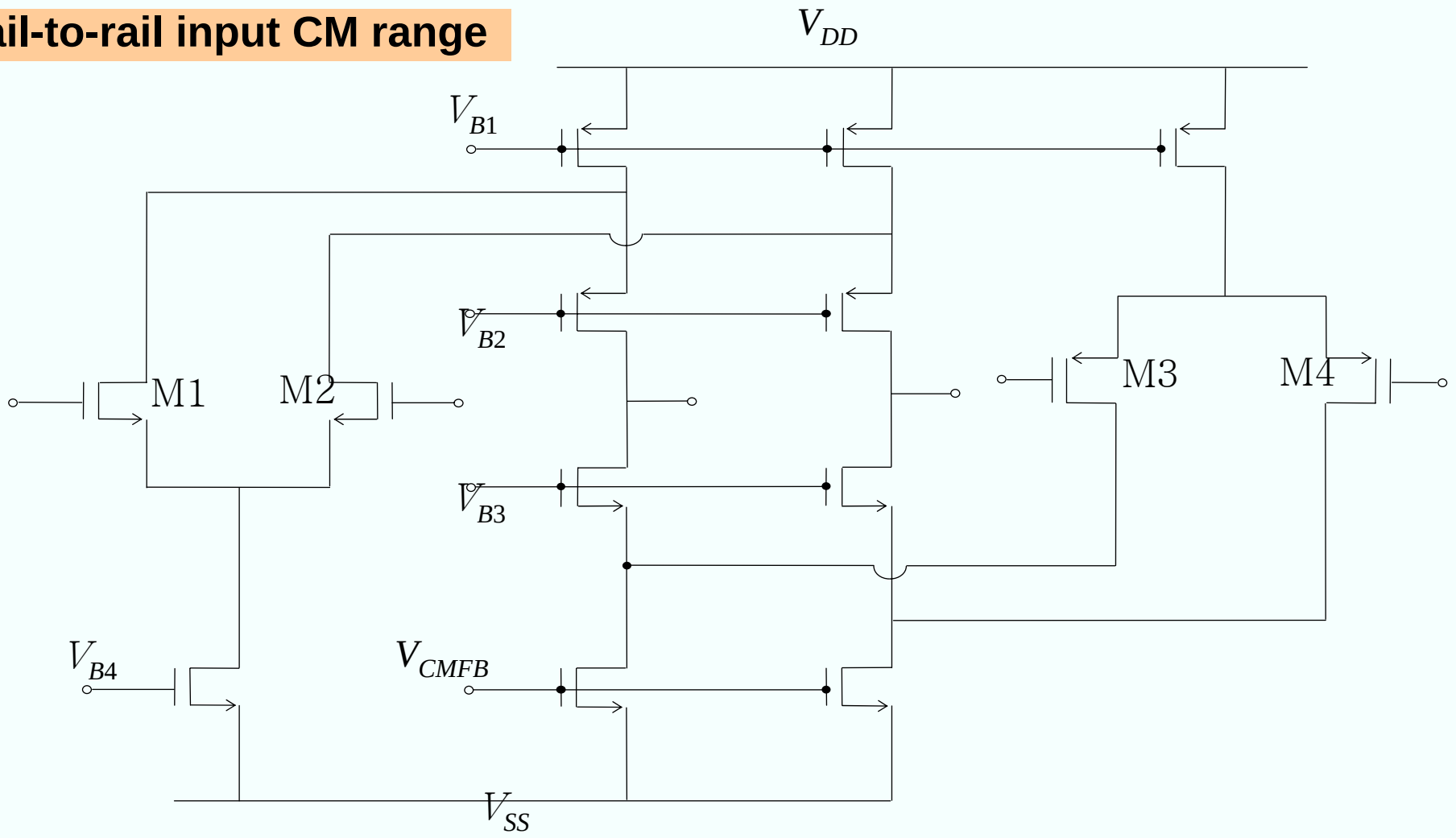
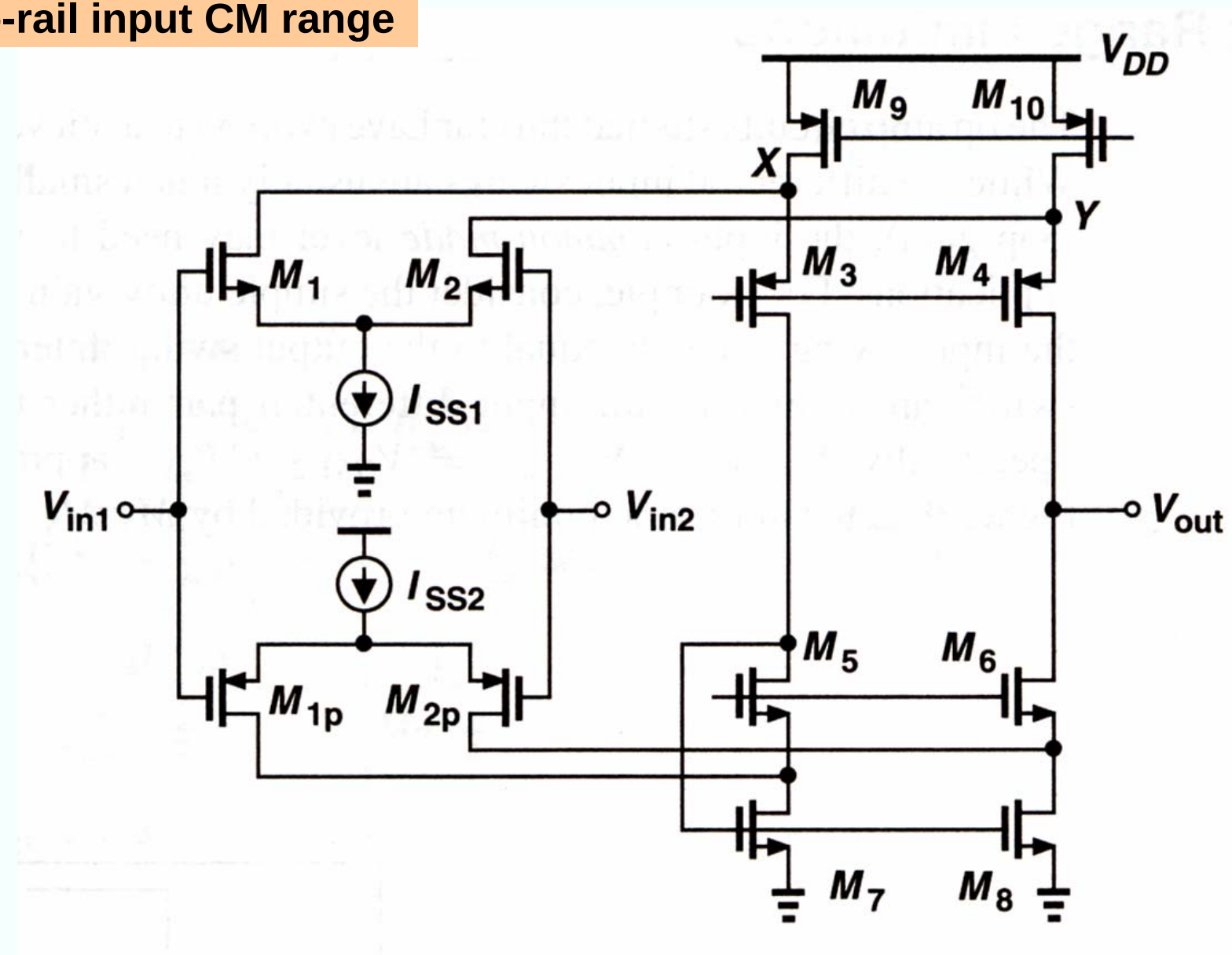


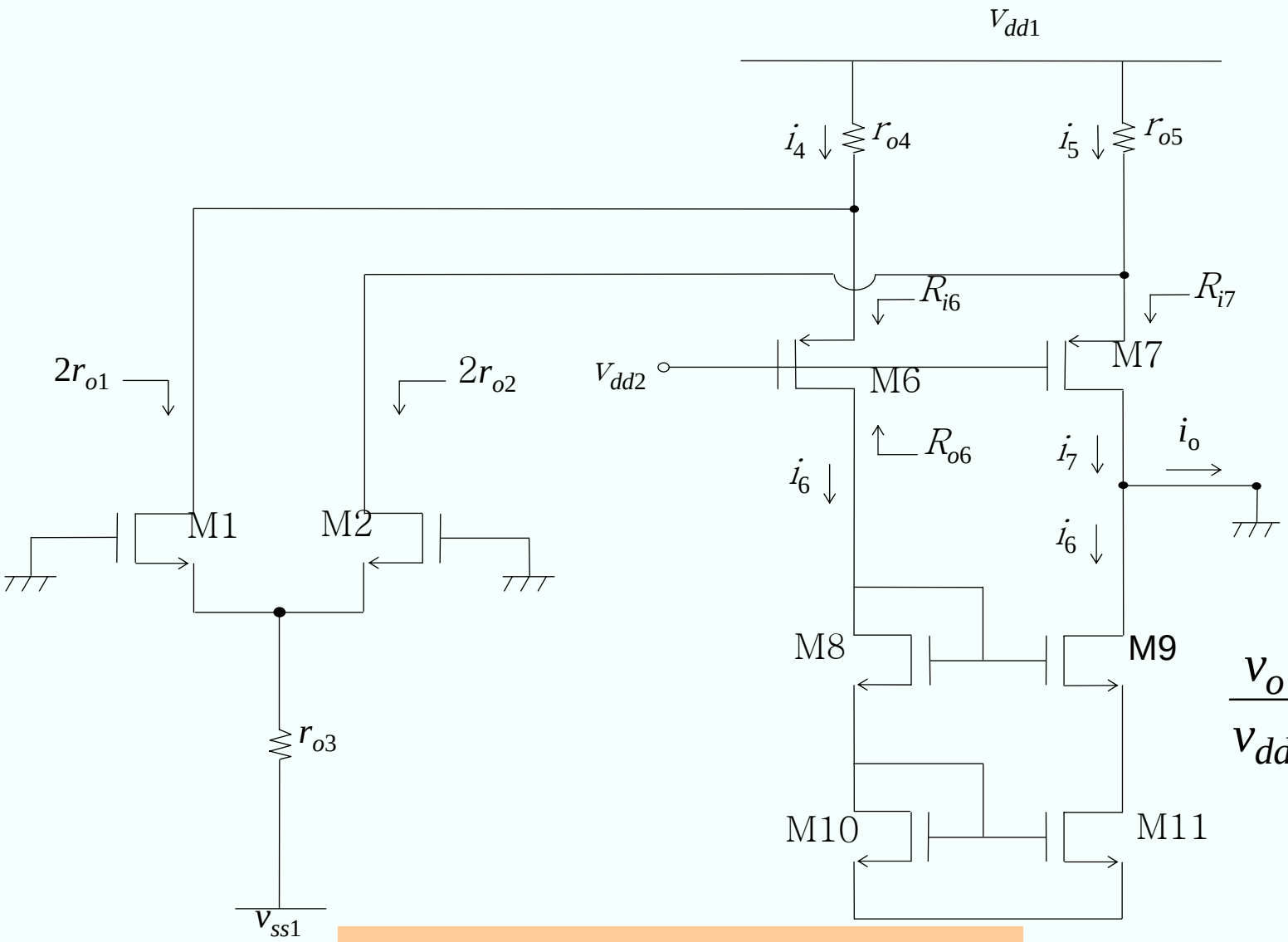
Fig 9.2.11 fully differential folded cascode CMOS OP amp with the rail-to-rail input common mode voltage range

Single ended folded cascode OP amp

Rail-to-rail input CM range



Low frequency PSRR (no mismatch)



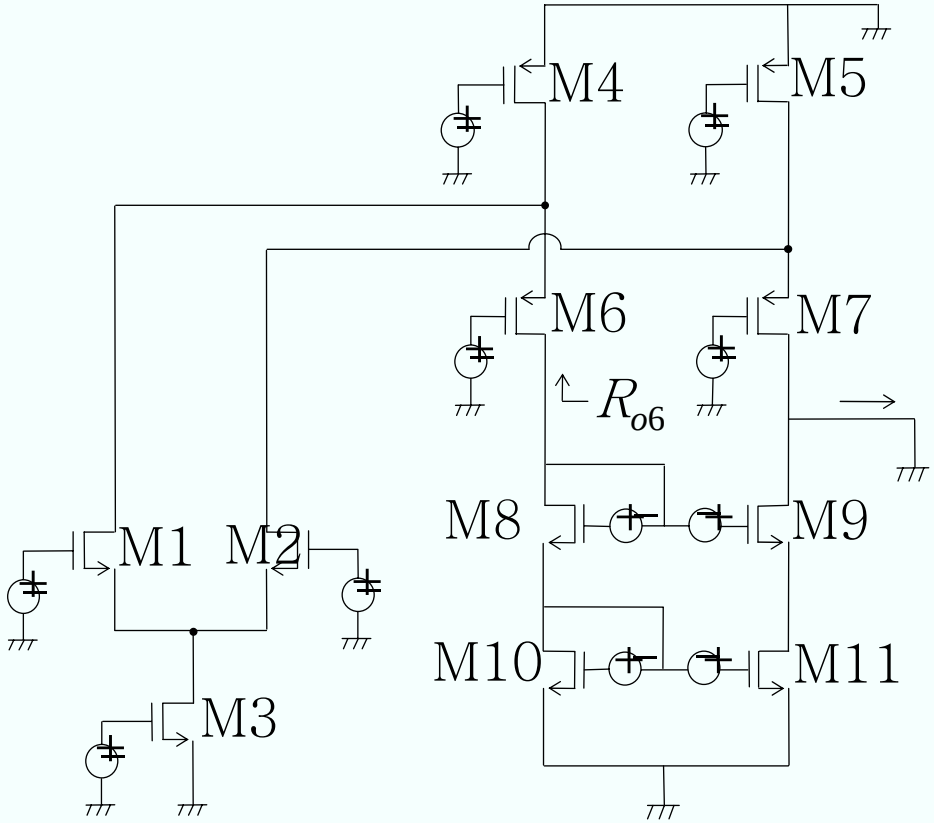
$$\left.\frac{v_o}{v_{dd}}\right|_{v_{ss}=0} = \frac{r_{o3}}{r_{o1}} \cdot A_{vc}$$

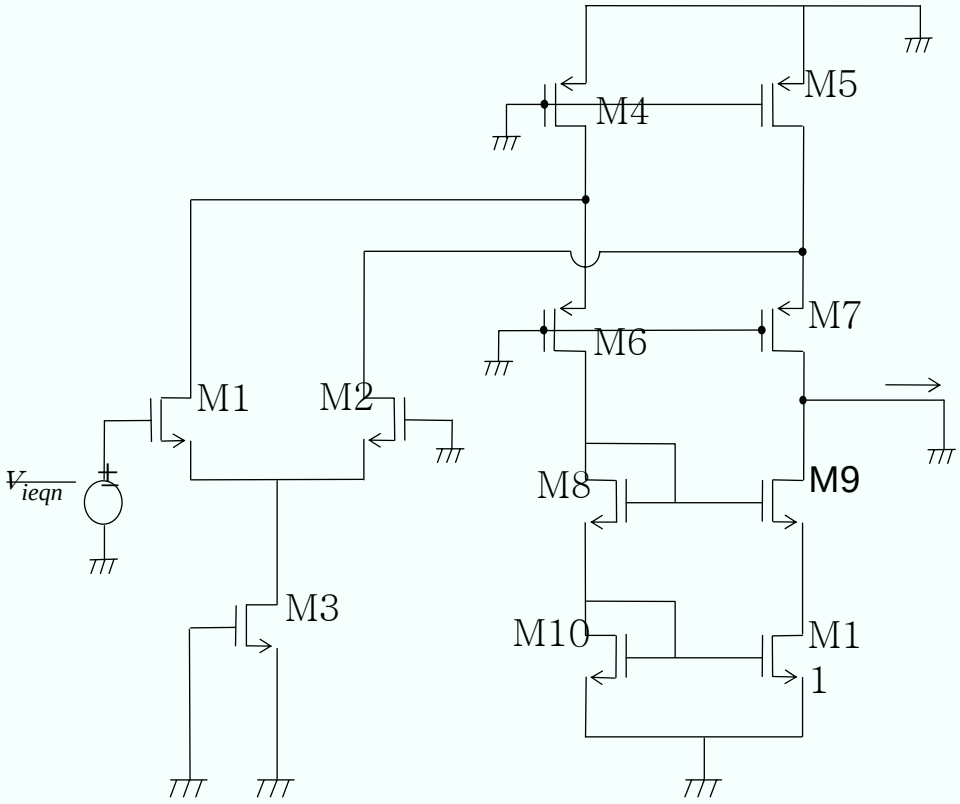
$$\left.\frac{v_o}{v_{ss}}\right|_{v_{dd}=0} = 1$$

PSRR+ ~= CMRR (very large)

PSRR- = Avd

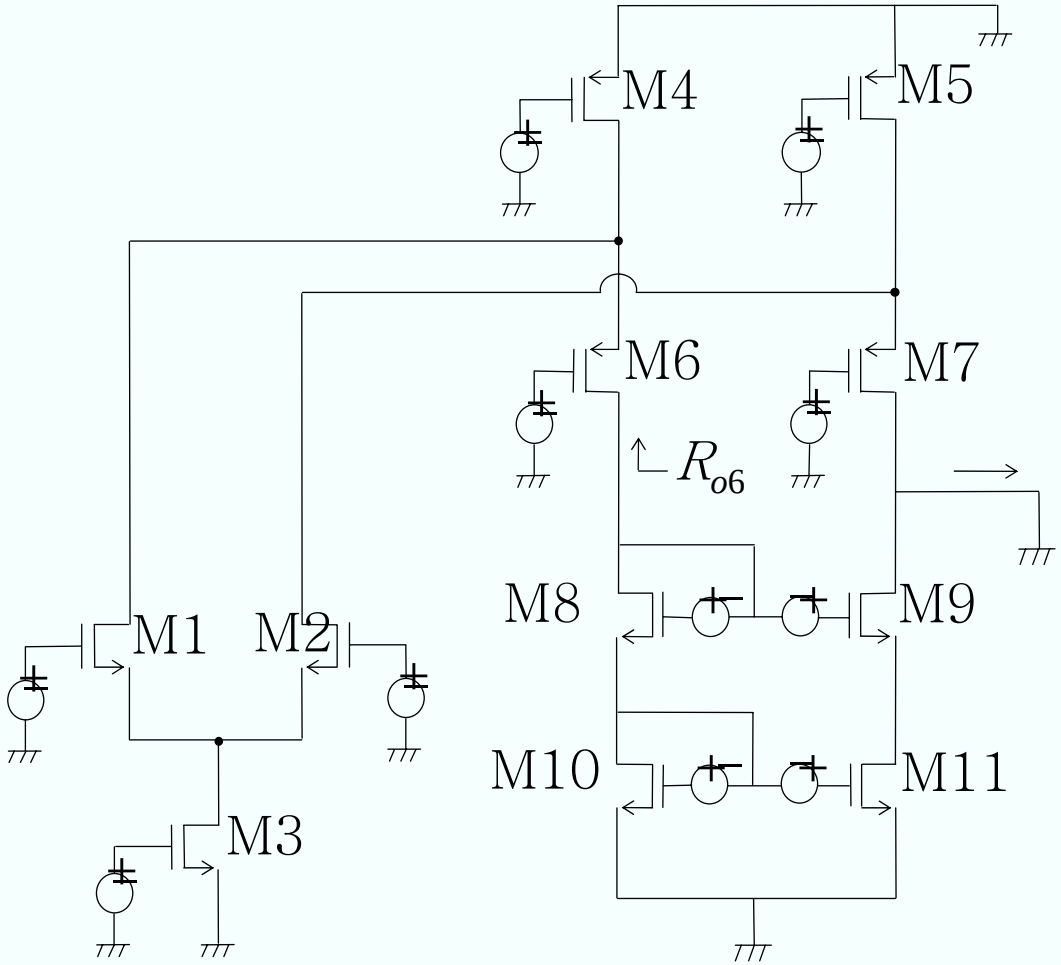
Equivalent Input Noise Voltage





$$\overline{v_{ieqn}^2} = \overline{v_{gn1}^2} + \overline{v_{gn2}^2} + \left(\frac{g_{m4}}{g_{m1}}\right)^2 \cdot \left(\overline{v_{gn4}^2} + \overline{v_{gn5}^2}\right) + \left(\frac{g_{m11}}{g_{m1}}\right)^2 \cdot \left(\overline{v_{gn10}^2} + \overline{v_{gn11}^2}\right)$$

Equivalent Input Noise Voltage



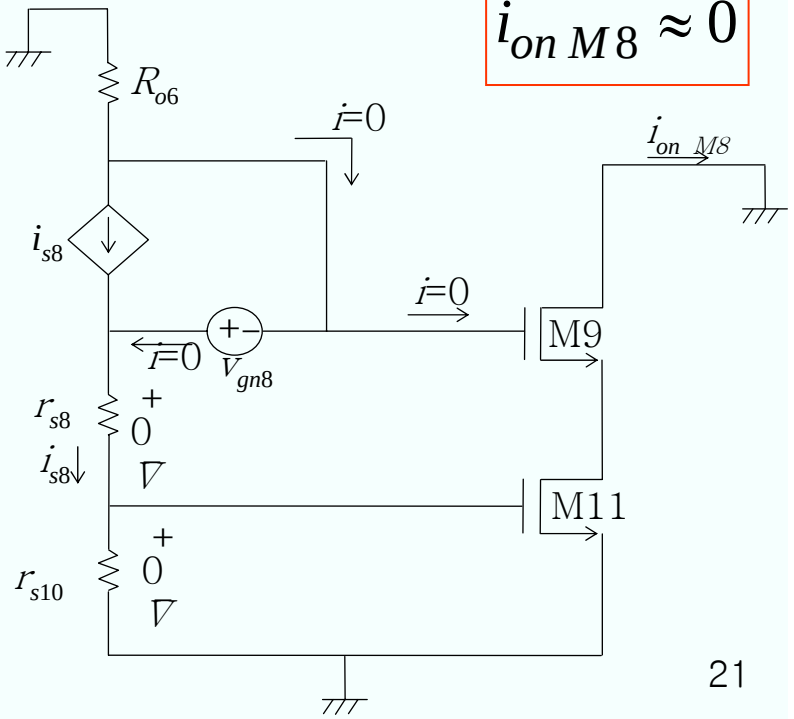
$$i_{on\,M4} = g_{m4} \cdot v_{gn4}$$

$$i_{on\,M5} = -g_{m5} \cdot v_{gn5} = -g_{m4} \cdot v_{gn5}$$

$$i_{on\,M6} = \frac{v_{gn6}}{r_{s6} + (r_{o4} \| 2r_{o1})} \cdot \left(1 + \frac{r_{o4}}{r_{o4} + 2r_{o1}}\right) \approx 0$$

$$i_{on\,M7} \approx 0$$

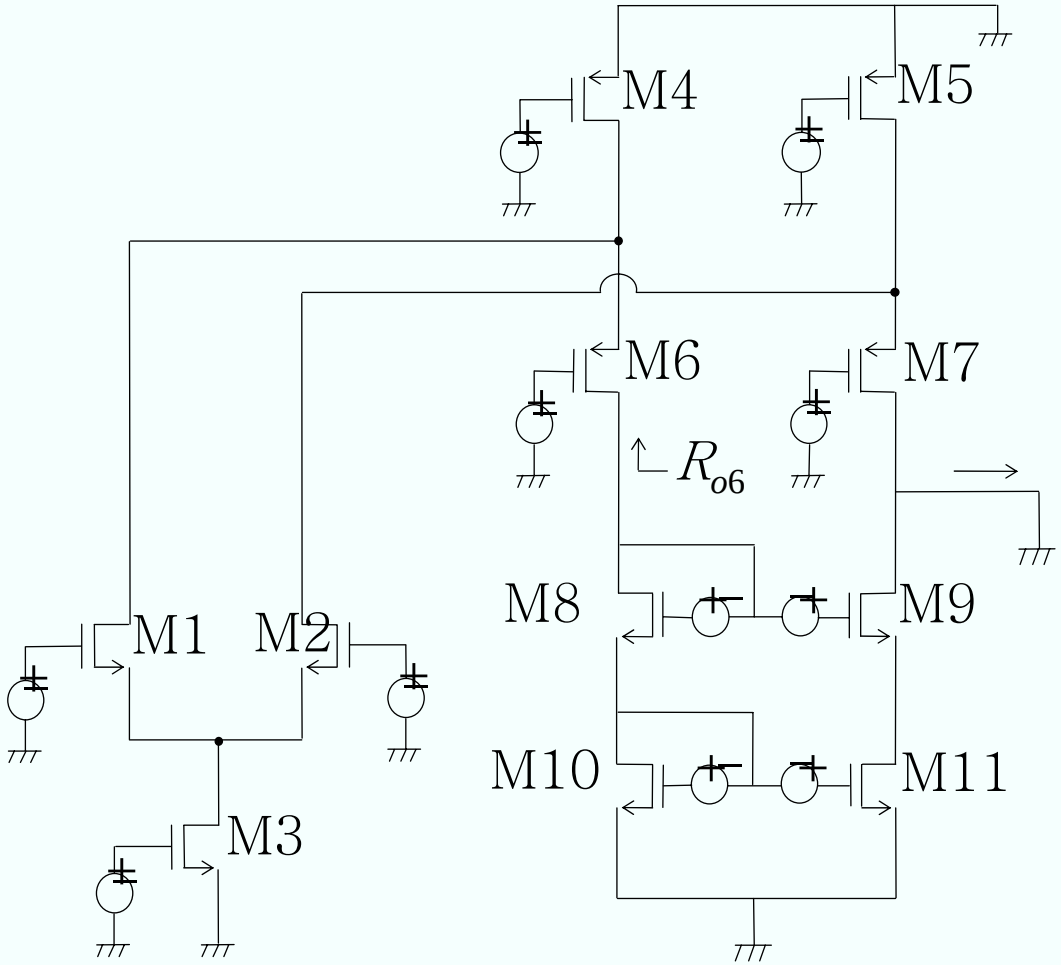
$$i_{on\,M8} \approx 0$$

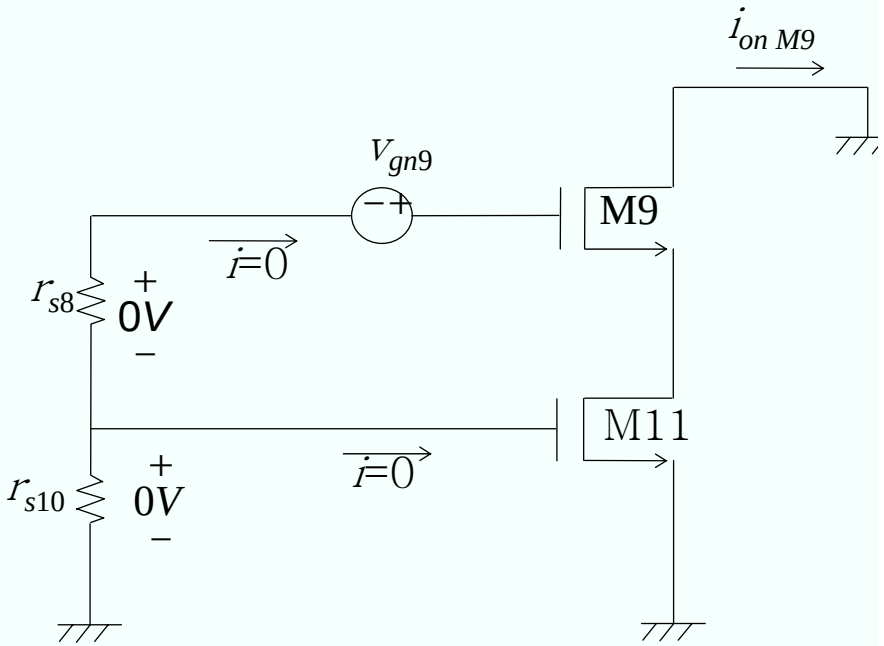


$$i_{on\,M1} = g_{m1} \cdot v_{gn1}$$

$$i_{on\,M2} = -g_{m2} \cdot v_{gn2} = -g_{m1} \cdot v_{gn1}$$

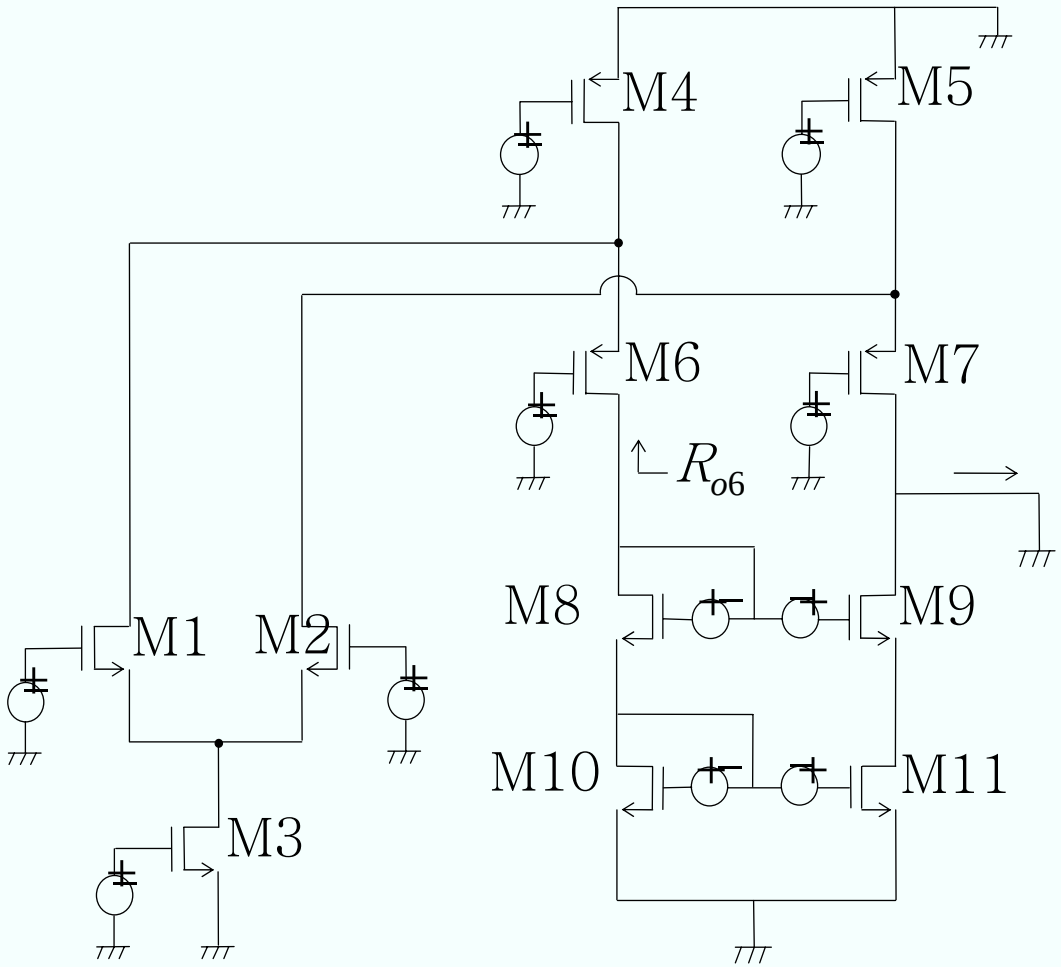
Equivalent Input Noise Voltage

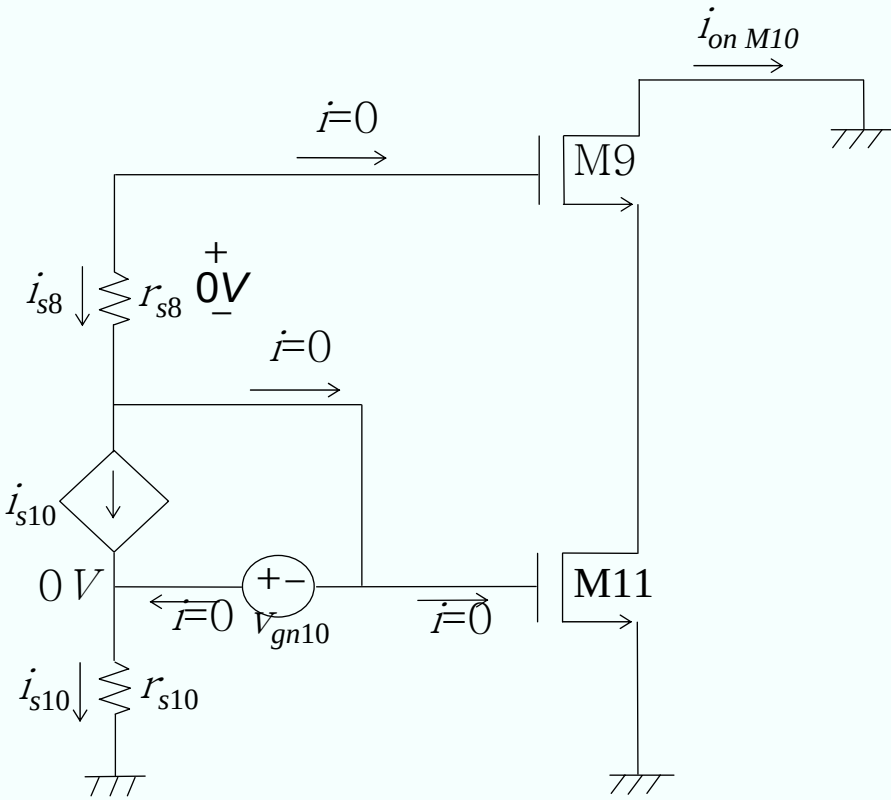




$$i_{on\ M9} = 0$$

Equivalent Input Noise Voltage



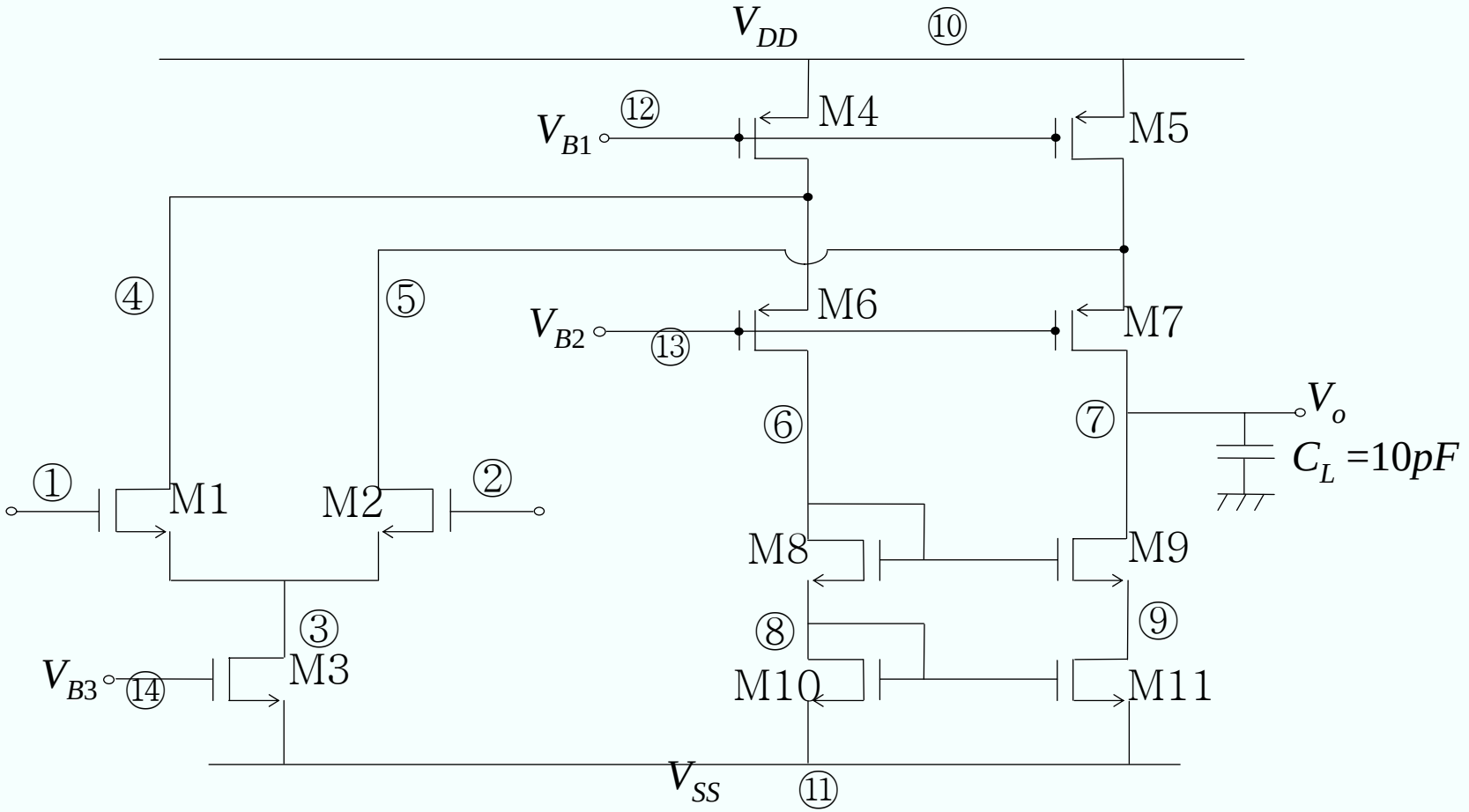


$$i_{on\ M10} = g_{m11} \cdot v_{gn10}$$

$$i_{on\ M11} = -g_{m11} \cdot v_{gn11}$$

$$\overline{v_{ieqn}^2} = \overline{v_{gn1}^2} + \overline{v_{gn2}^2} + \left(\frac{g_{m4}}{g_{m1}}\right)^2 \cdot \left(\overline{v_{gn4}^2} + \overline{v_{gn5}^2}\right) + \left(\frac{g_{m11}}{g_{m1}}\right)^2 \cdot \left(\overline{v_{gn10}^2} + \overline{v_{gn11}^2}\right)$$

Frequency response

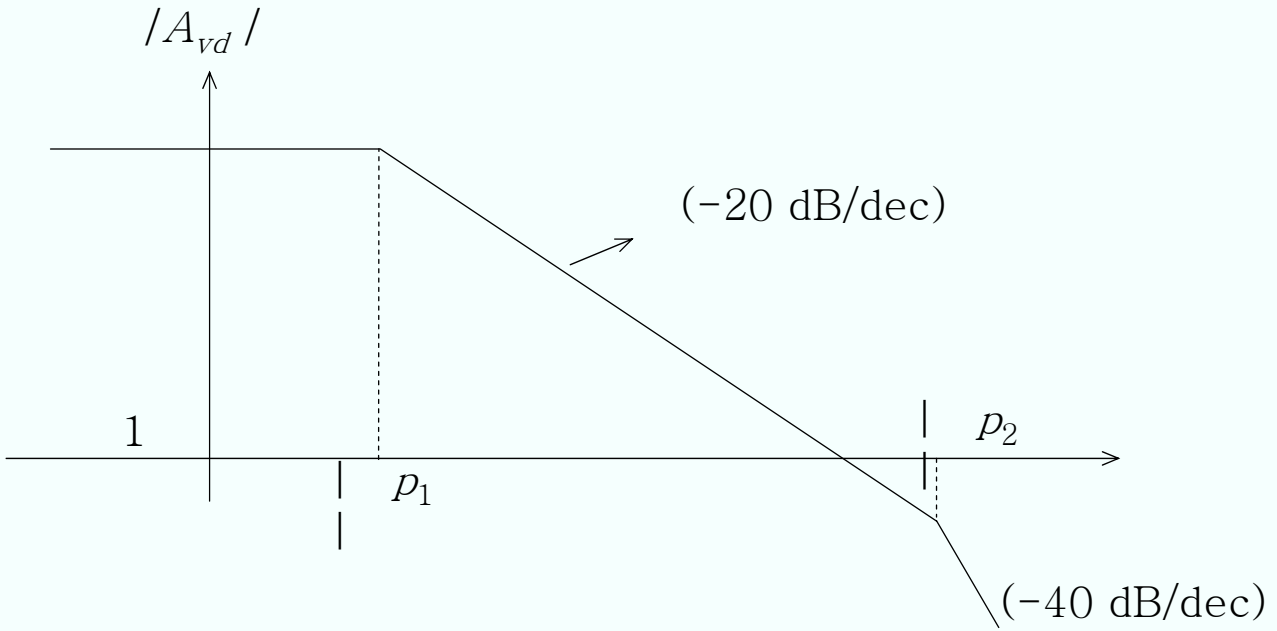


High Impedance Node : output node only

$$|p_1| = \frac{1}{R_o \cdot C_L}$$

$$|p_2| \approx \frac{1}{r_{s6} \cdot \left\{ C_{GS\,6} + C_{GSOV\,6} + C_{BS6} + C_{BD1} + C_{GDOV\,4} + C_{BD\,4} + C_{GDOV\,1} \cdot \left(1 + \frac{g_{m6}}{g_{m1}} \right) \right\}}$$

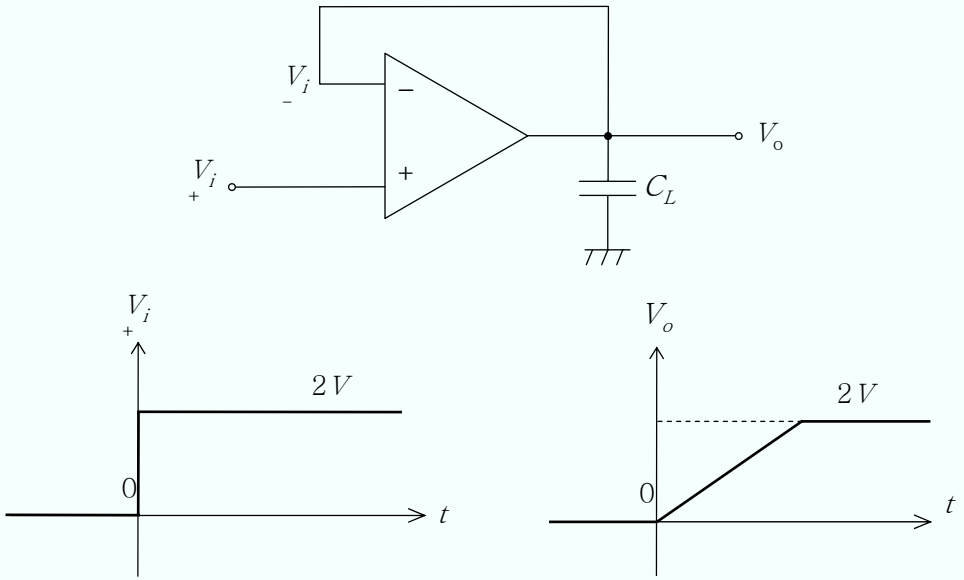
Frequency response



$$A_{vd} = g_{m1}R_o \qquad |p_1| = \frac{1}{R_o C_L} \qquad \omega_T = \frac{g_{m1}}{C_L} \qquad |p_2| = \frac{1}{r_{s6}C_6}$$

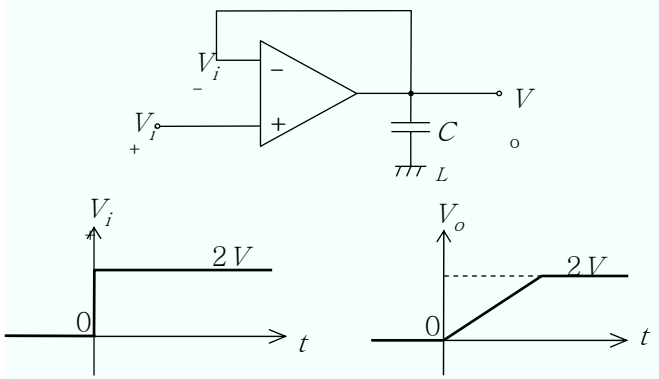
increase CL ➔ decrease p1, no effect on p2

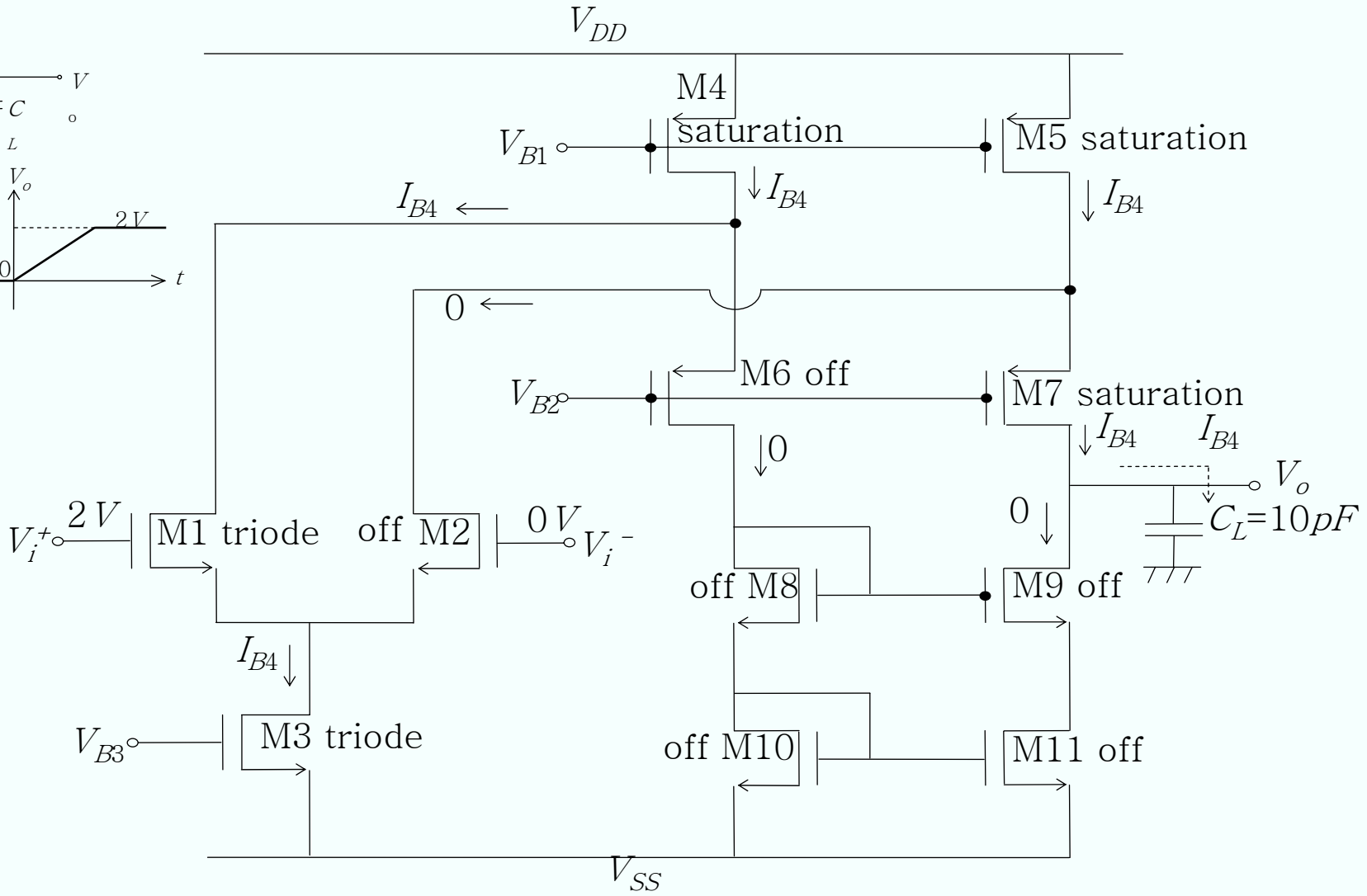
Slew rate



Slew : non-linear behavior

Slew rate



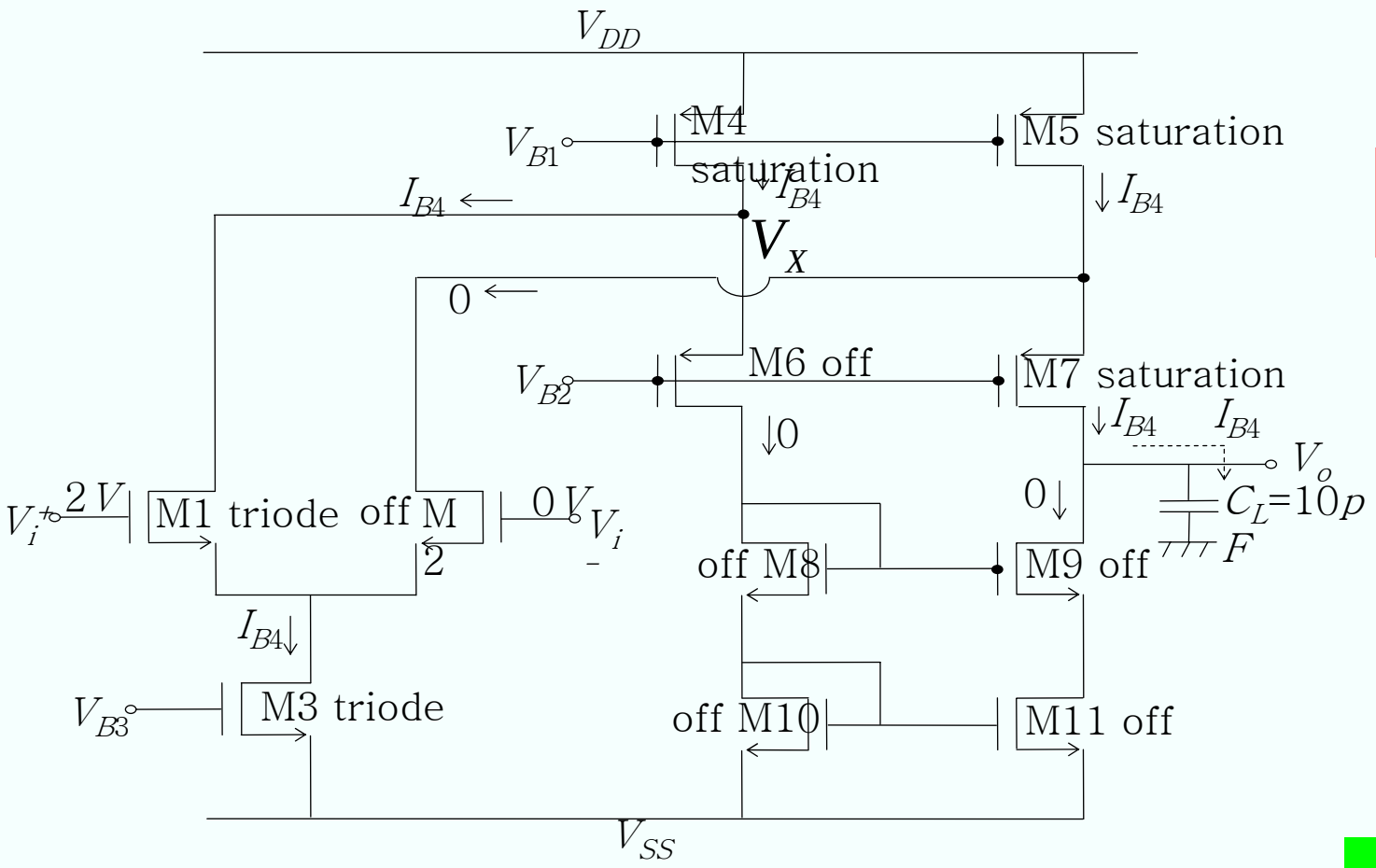


$$I_{B3} > I_{B4} > 0.5 I_{B3}$$

$$V_o(t) = \frac{I_{B4}}{C_L} \cdot t$$

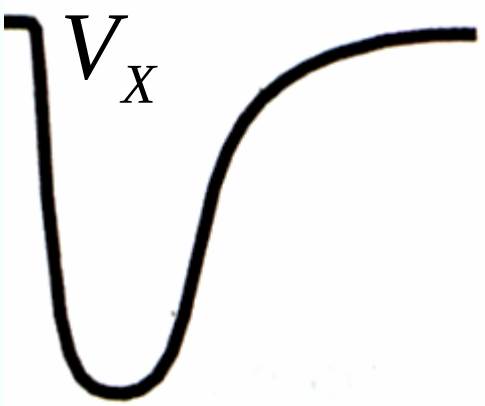
$$SR^+ \triangleq \left.\frac{dV_o}{dt}\right|_{\max} = \frac{I_{B4}}{C_L}$$

Slew rate



$$I_{B3} > I_{B4} > 0.5 I_{B3}$$

Droop in VX

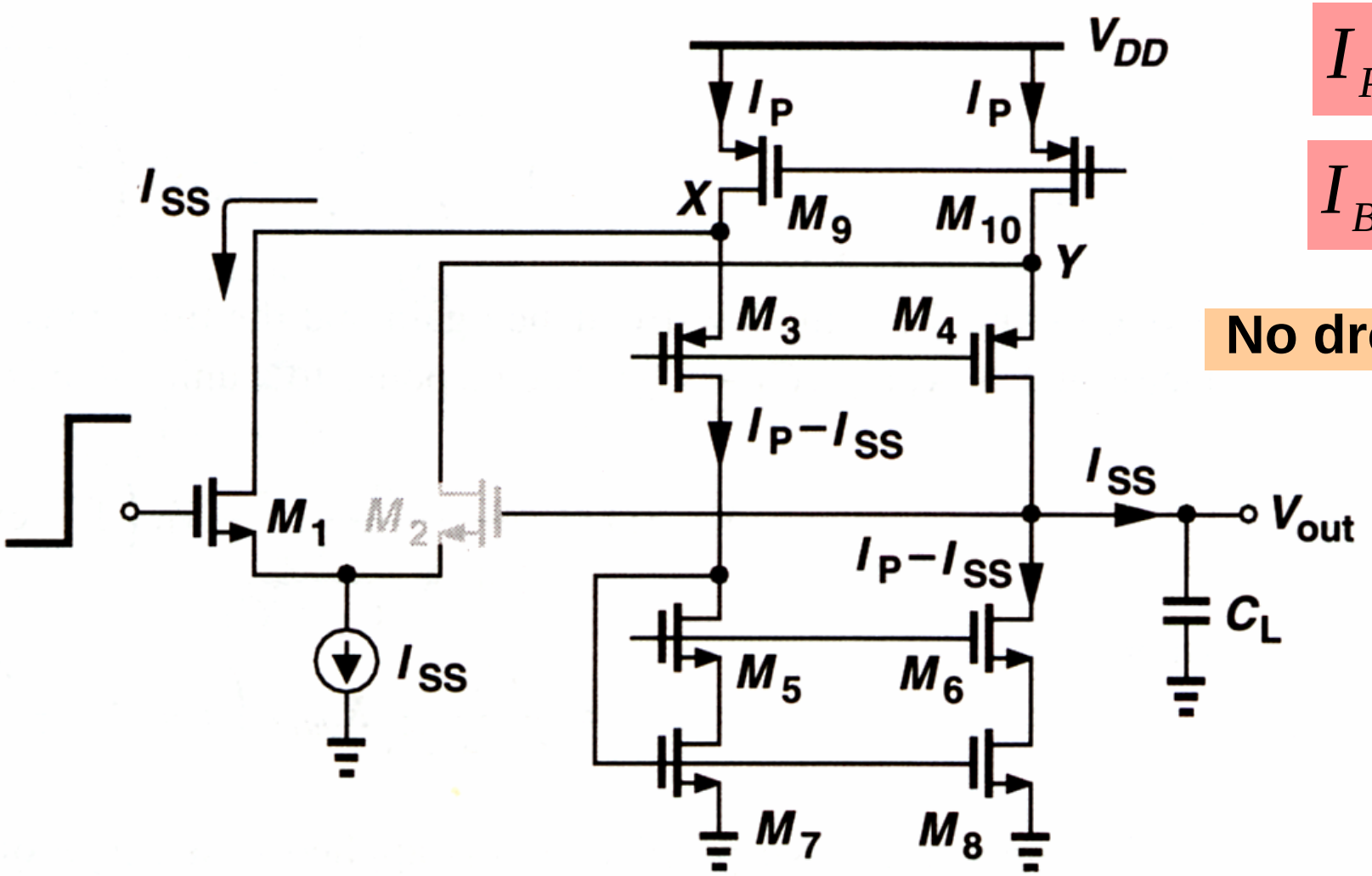


Slow in settling

$$V_o(t) = \frac{I_{B4}}{C_L} \cdot t$$

$$SR^+ \triangleq \left.\frac{dV_o}{dt}\right|_{\max} = \frac{I_{B4}}{C_L}$$

Slew rate



$$I_P > I_{SS}$$

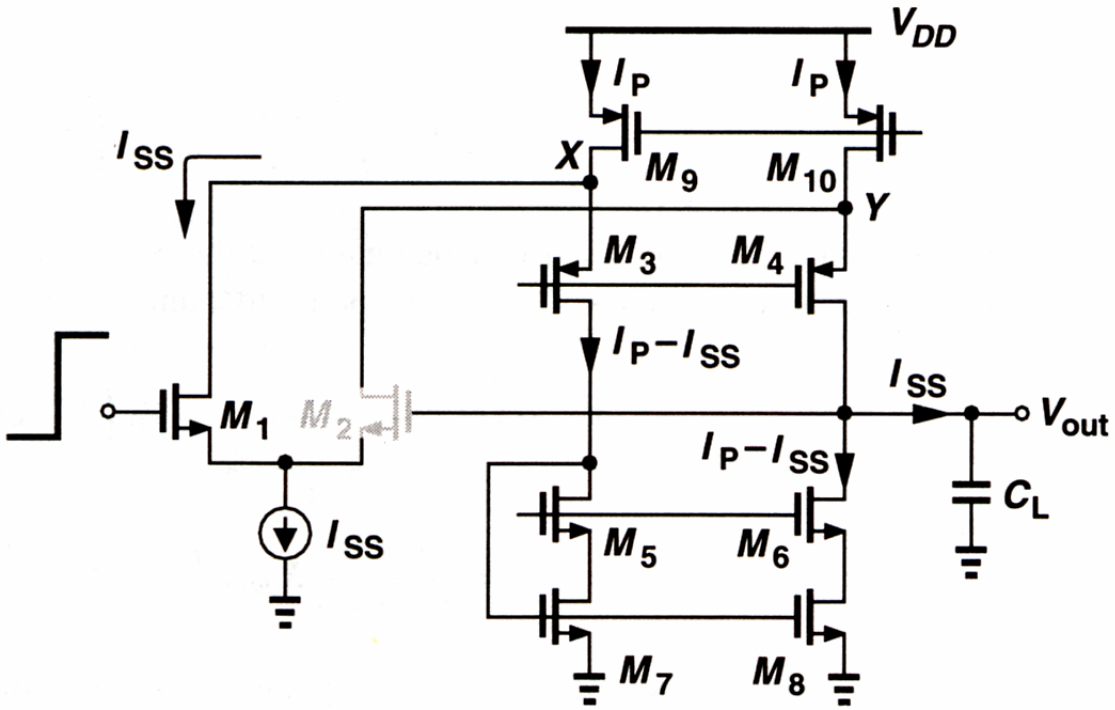
$$I_{B4} > I_{B3}$$

No droop in VX, VY

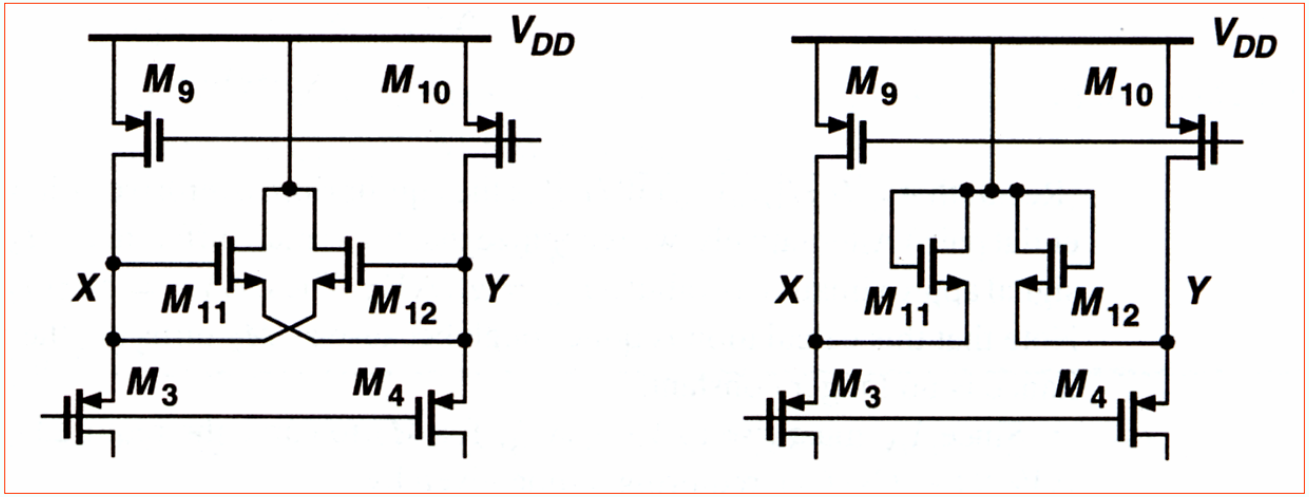
$$V_o(t) = \frac{I_{SS}}{C_L} \cdot t = \frac{I_{B3}}{C_L} \cdot t$$

$$SR^+ \triangleq \left.\frac{dV_o}{dt}\right|_{\max} = \frac{I_{SS}}{C_L} = \frac{I_{B3}}{C_L}$$

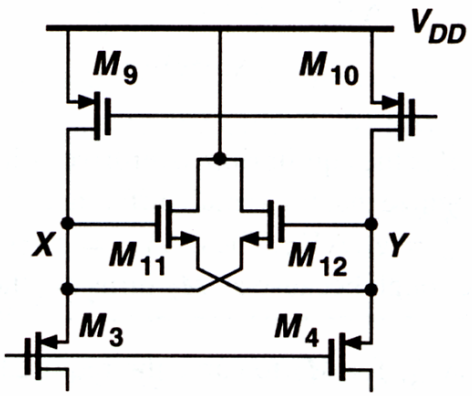
VX droop prevention circuit

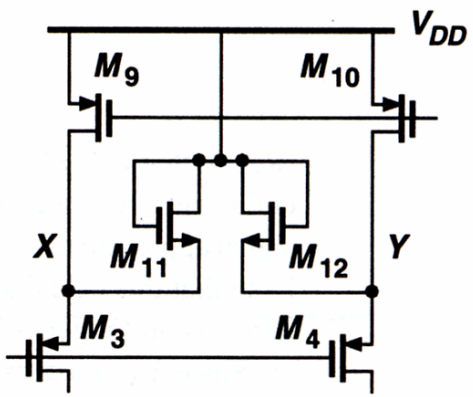


Increase slew rate by supplying extra current during slewing

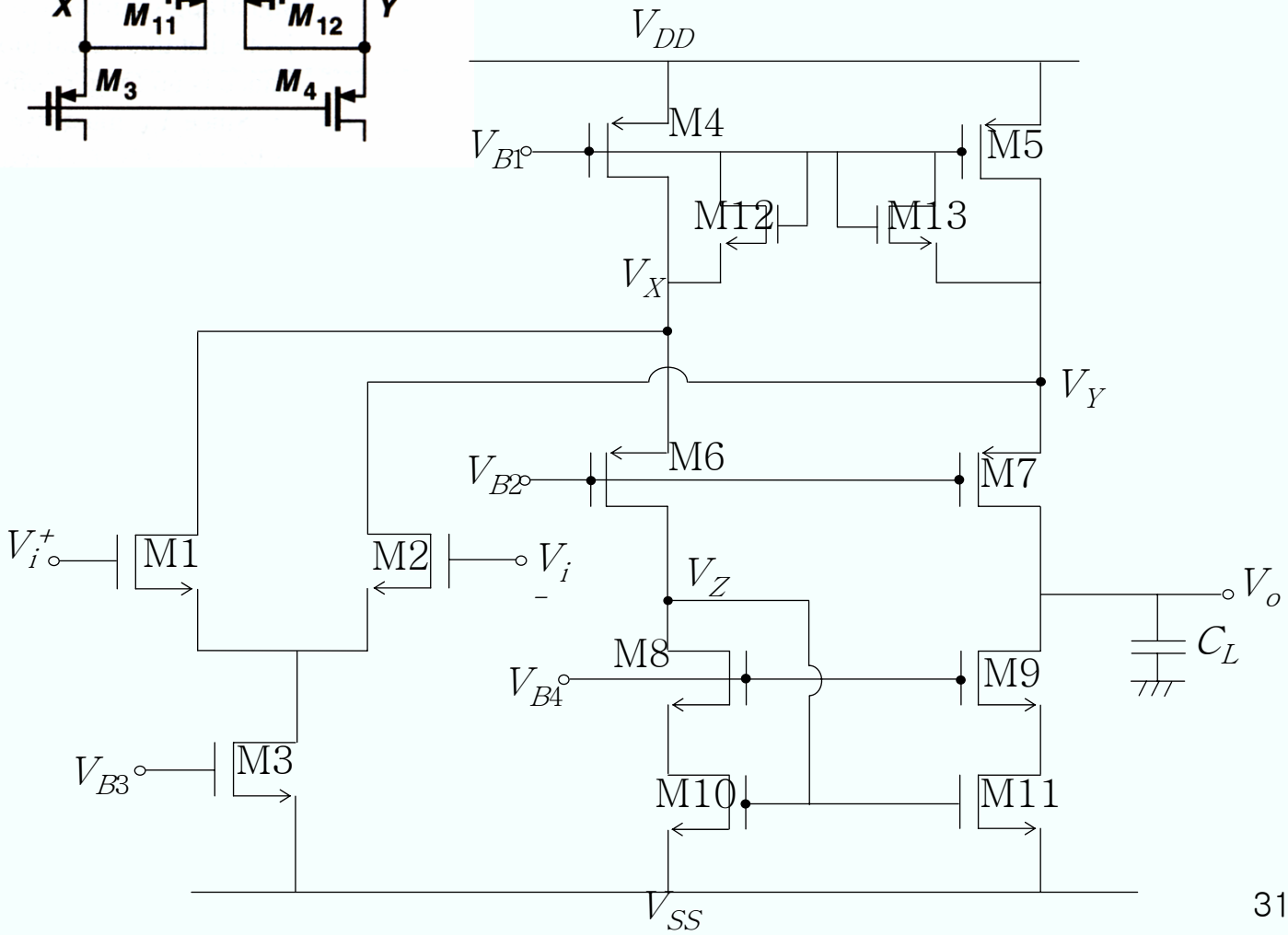


VX droop prevention circuit





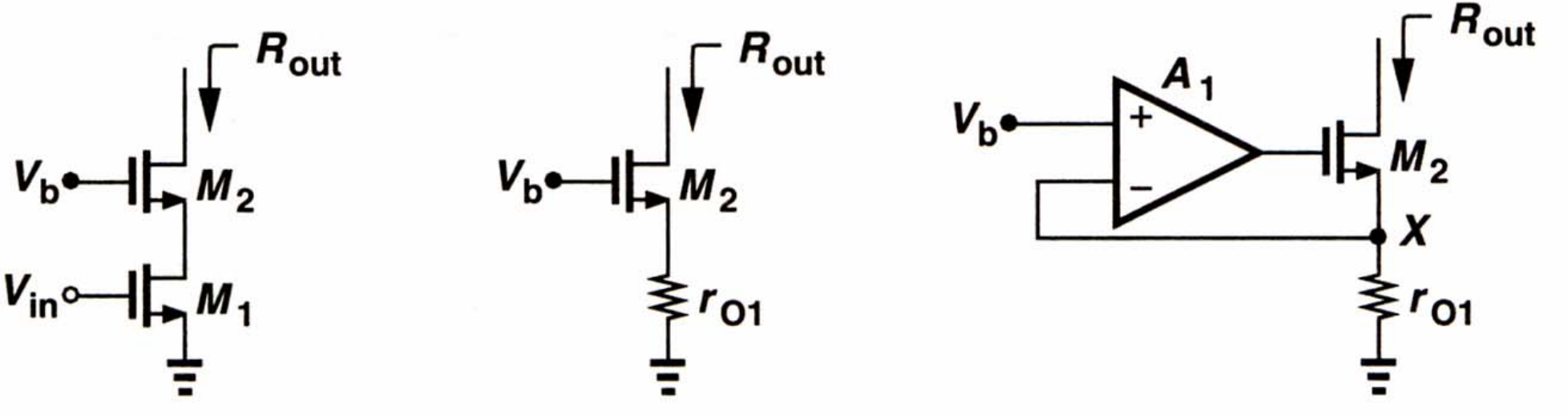
Increase slew rate by supplying extra current during slewing



Gain-boosted cascode OP amp

Increase gain of 1-stage cascode OP amp by gain-boosting

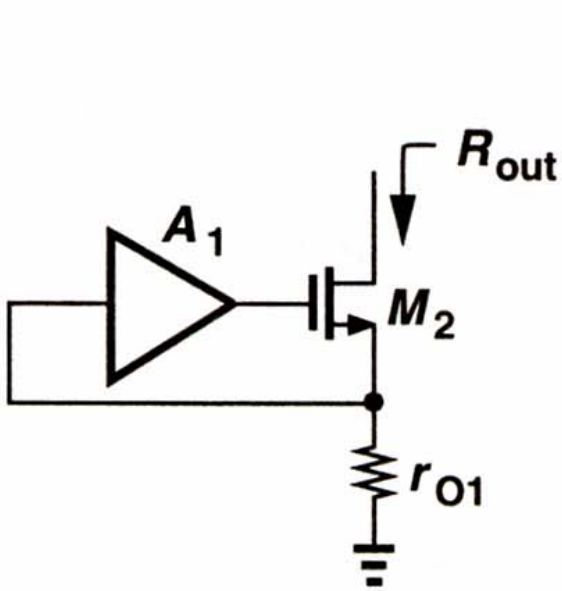
gain-boosting of cascode amp

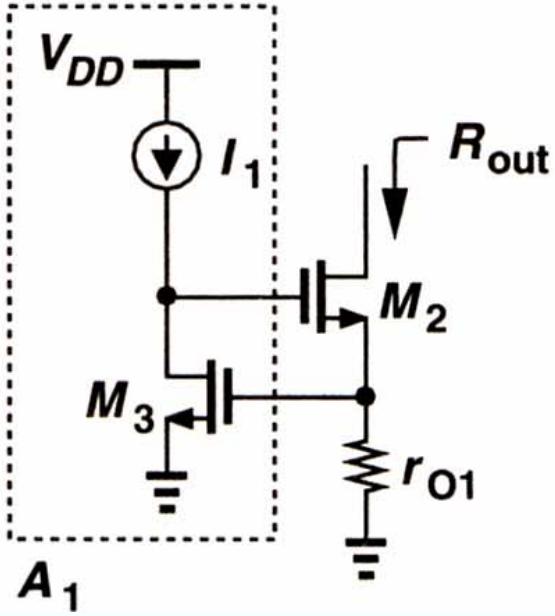


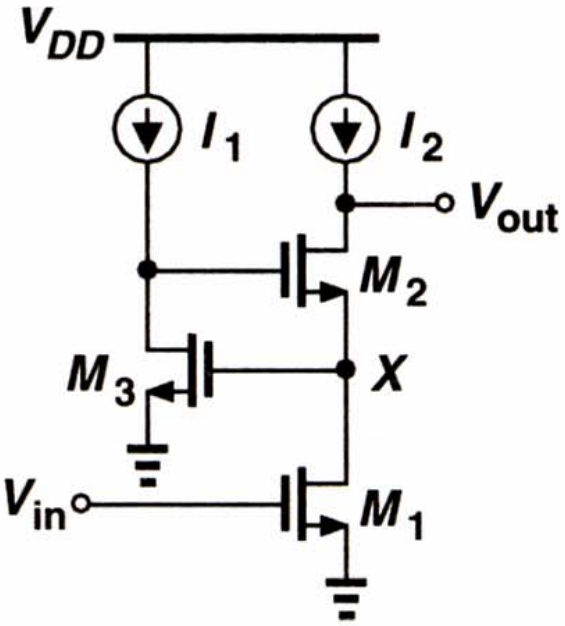
$$A_v = g_{m1} R_{out} \qquad R_{out} \approx A_1 g_{m2} r_{o2} r_{o1}$$

Gain-boosted cascode OP amp

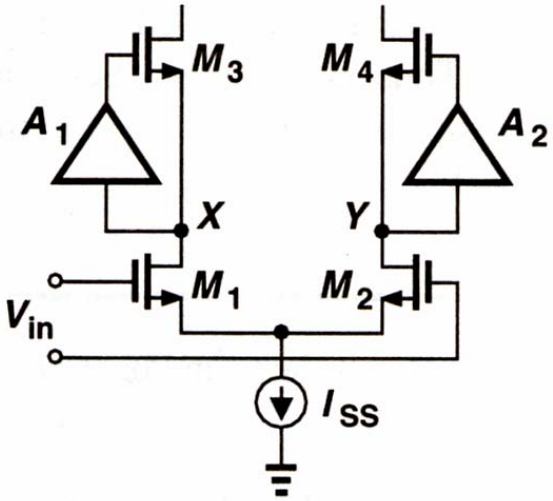
gain-boosting of cascode amp

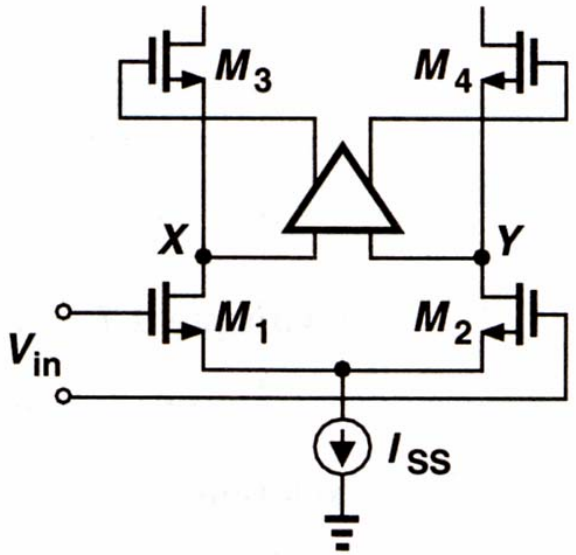


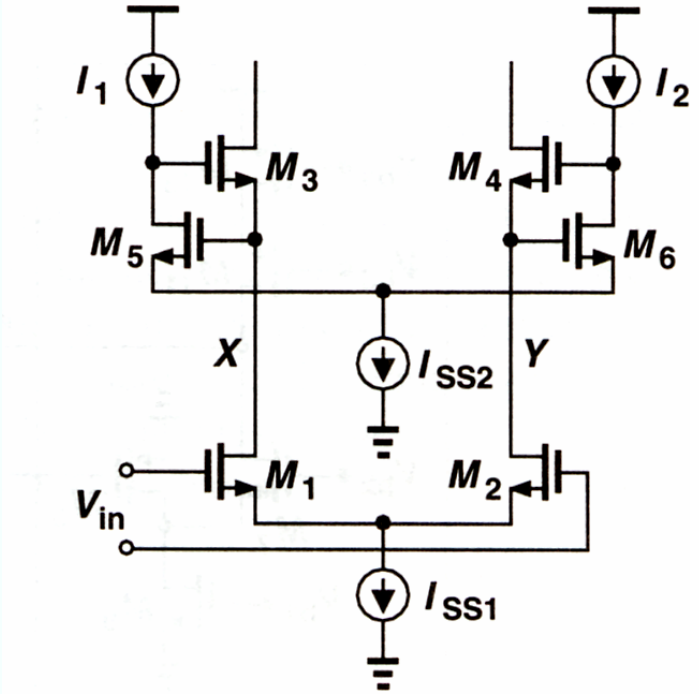




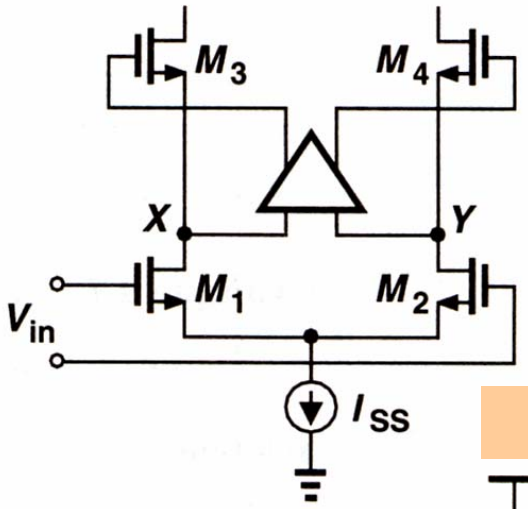
Gain-boosted cascode OP amp



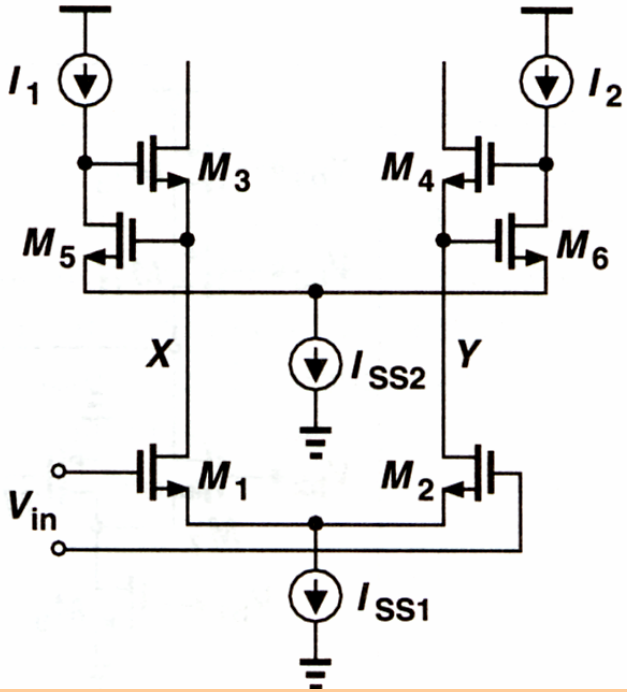




Gain-boosted cascode OP amp

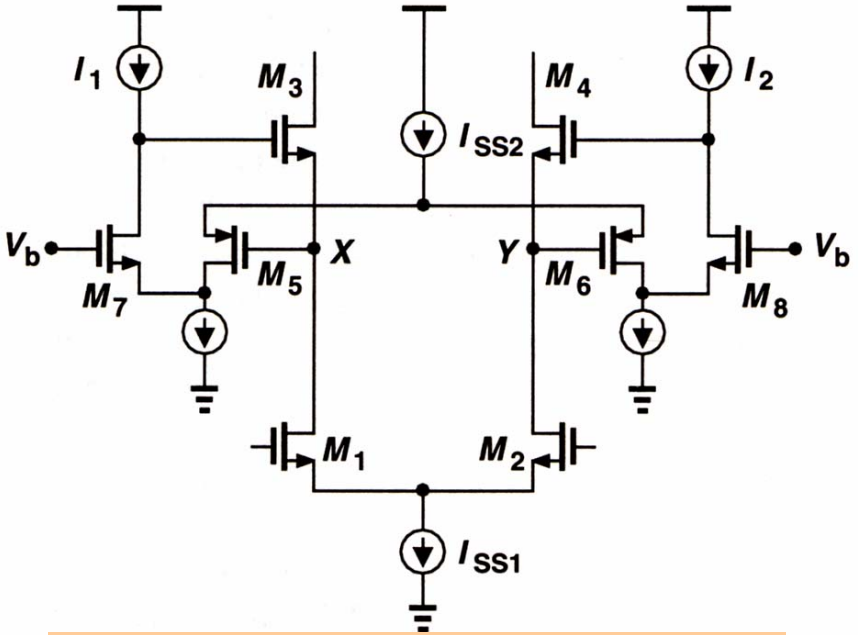


Limited output range



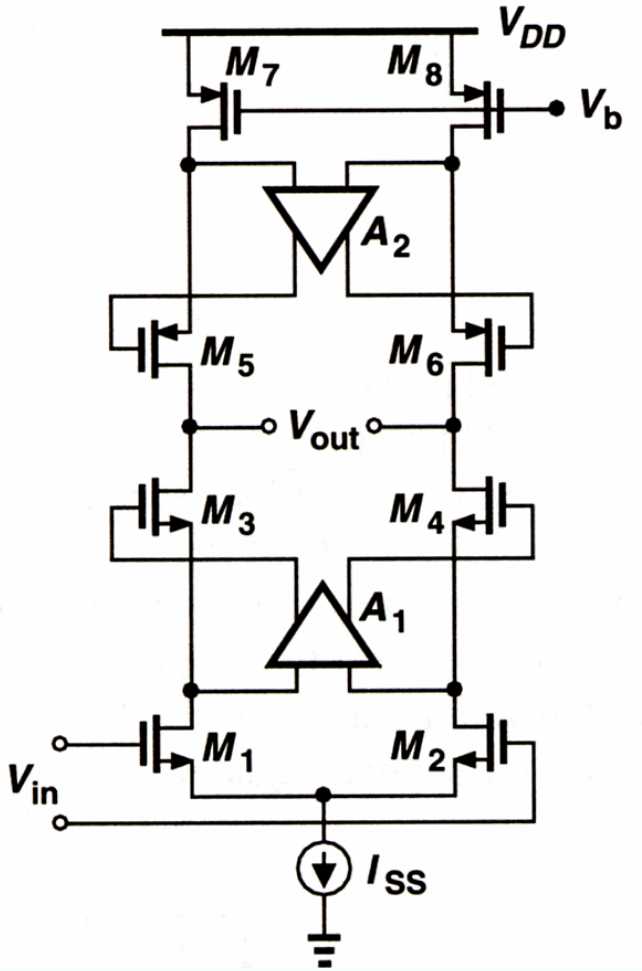
Min Vout : VDSAT(ISS2)+VDSAT5+VDSAT3+VTH5

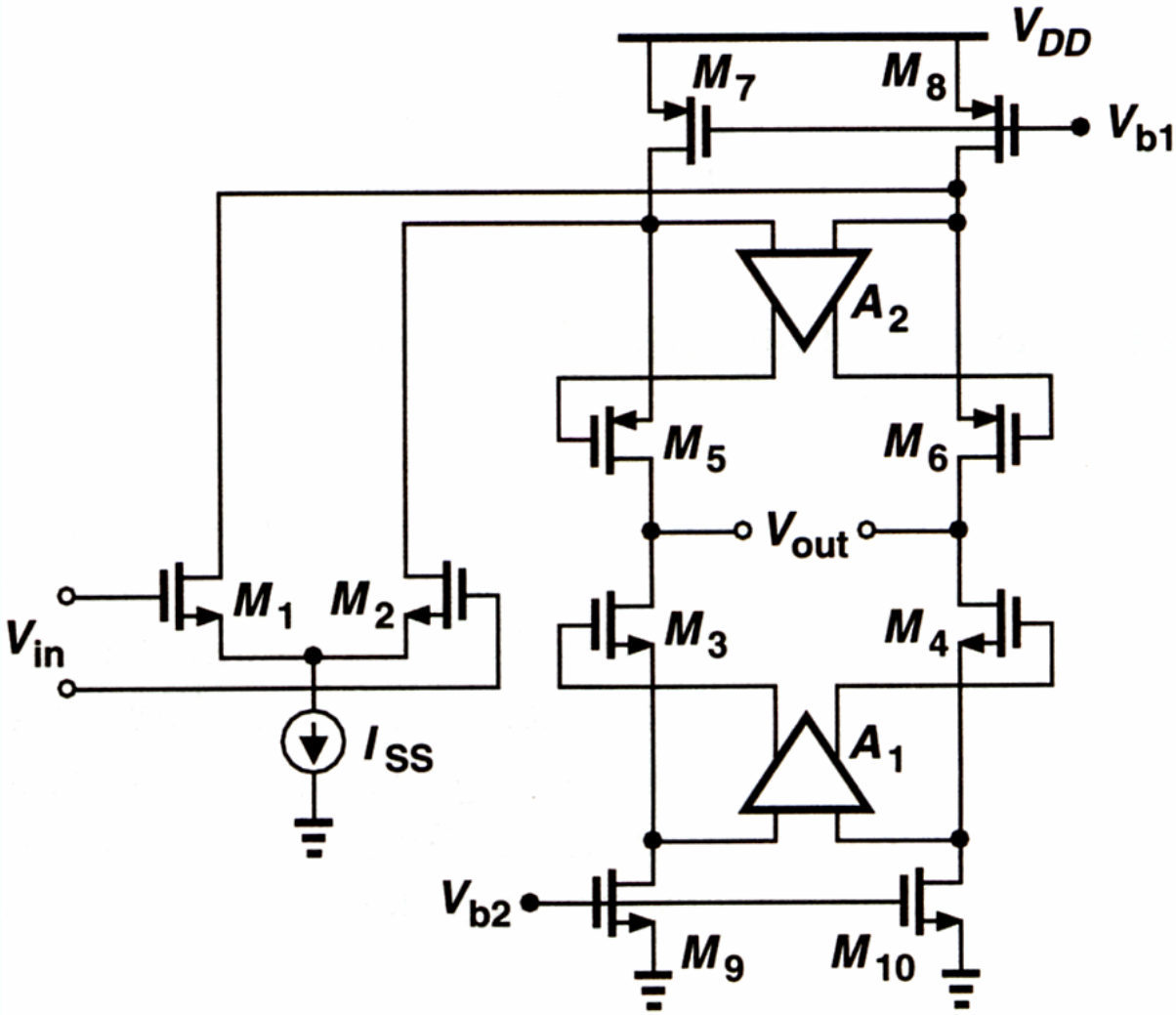
Improved output range



Min Vout : VDSAT(ISS1)+VDSAT1+VDSAT3

Gain-boosted cascode OP amp



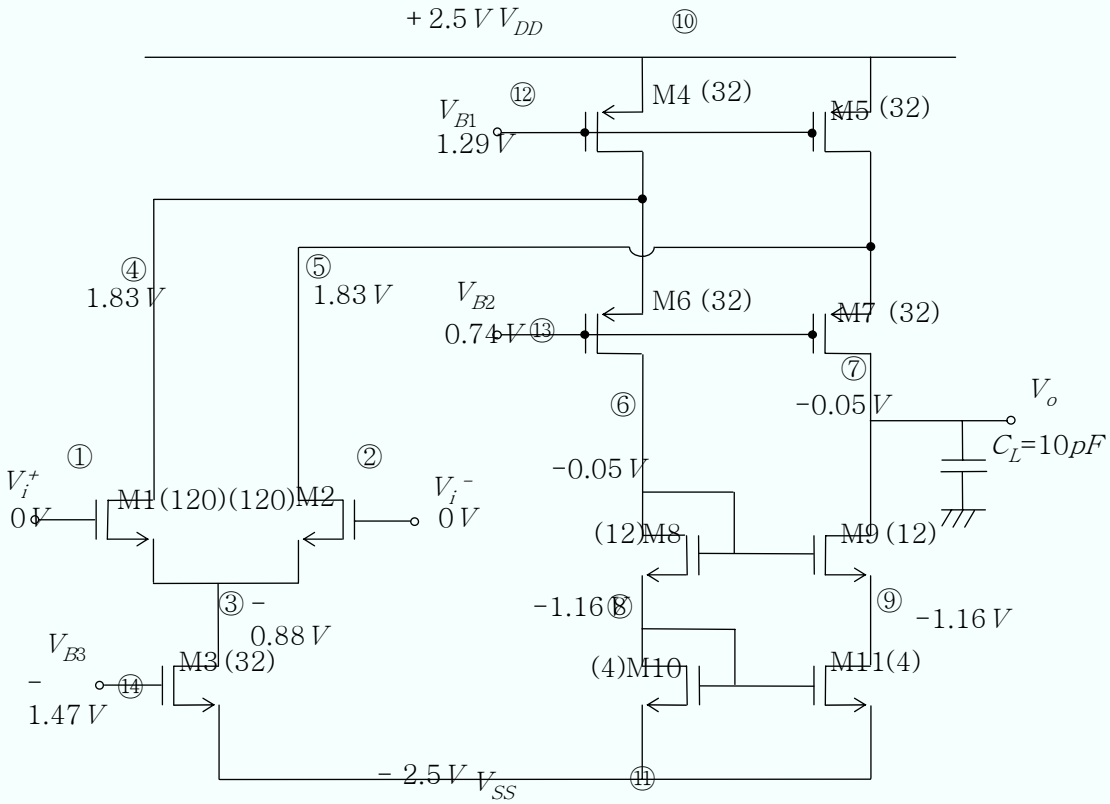


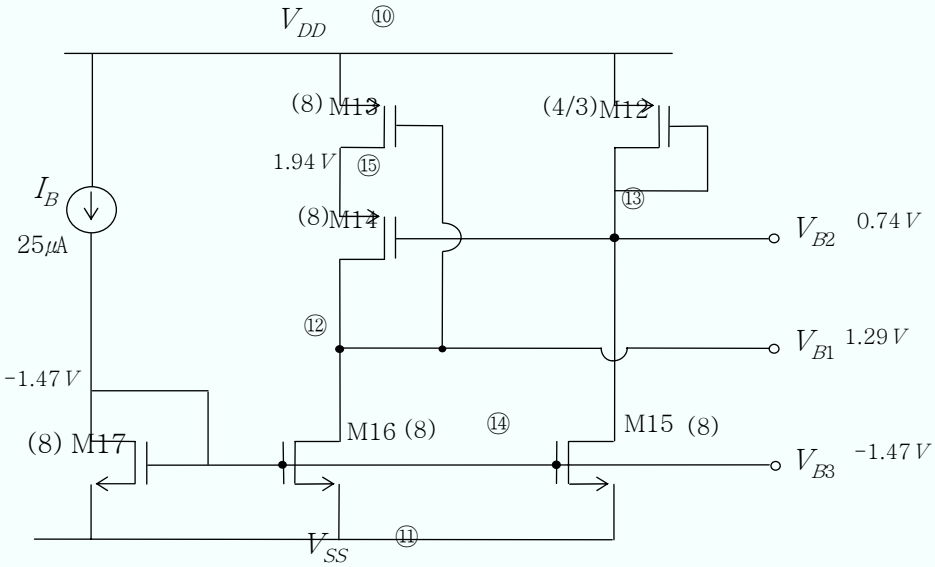
Frequency response: not much degraded by gain-boosting amp (due to only error signal passes gain-boosting amp)

Comparison of OP amps

	Gain	Output Swing	Speed	Power Dissipation	Noise
Telescopic	Medium	Medium	Highest	Low	Low
Folded-Cascode	Medium	Medium	High	Medium	Medium
Two-Stage	High	Highest	Low	Medium	Low
Gain-Boosted	High	Medium	Medium	High	Medium

SPICE simulation: Folded cascode OP amp





L=1.2um

SPICE simulation: Folded cascode OP amp

	식	계산 값	SPICE
G_{md} [Siemens]	g_{m1}	1.28×10^{-3}	1.24×10^{-3}
G_{mc} [Siemens]	$-\dfrac{r_{s8}+r_{s10}}{g_{m6}r_{o6}\cdot(r_{o1}\parallel r_{o4})\cdot 2r_{o3}}$	-4.12×10^{-9}	-5.00×10^{-9}
R_o [Ω]	$\{g_{m7}r_{o7}\cdot(r_{o2}\parallel r_{o5})\}\parallel g_{m9}r_{o9}r_{o1}\}$	4.17×10^{6}	4.33×10^{6}

SPICE simulation: Folded cascode OP amp

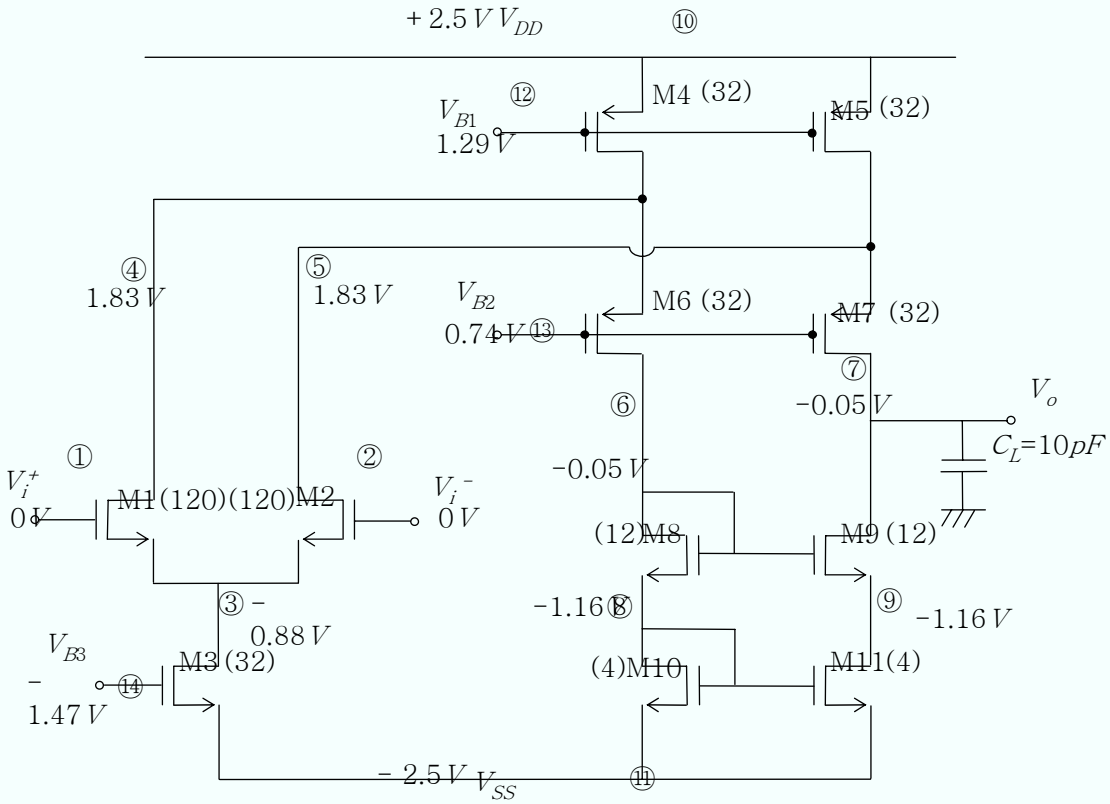
$A_{vd}\ [V/V]$ $([dB])$	$G_{md} \cdot R_o$	5.34×10^{3} $(74.6dB)$	5.38×10^{3} $(74.6dB)$
$A_{vc}\ [V/V]$ $([dB])$	$G_{mc} \cdot R_o$	-1.72×10^{-2} $(-35.3dB)$	-2.17×10^{-2} $(-33.3dB)$
$\frac{\partial V_o}{\partial V_{DD}}\ [V/V]$	$\frac{r_{o3}}{r_{o1}} \cdot A_{vc}$	-7.98×10^{-3}	4.50×10^{-2} $(*)7.57\times10^{-4}$
$\frac{\partial V_o}{\partial V_{SS}}\ [V/V]$	1	1	0.998 $(*)\ 1.02$
$CMRR\ [\cdots]$	$\left\lvert \frac{A_{vd}}{A_{vc}} \right\rvert$	3.11×10^{5} $(110dB)$	2.48×10^{5} $(108dB)$
$PSRR^{+}$	$\frac{A_{vd}}{\left\lvert \frac{\partial V_o}{\partial V_{DD}} \right\rvert}$	6.69×10^{5} $(117dB)$	1.20×10^{5} $(102dB)$
$PSRR^{-}$	$\frac{A_{vd}}{\left\lvert \frac{\partial V_o}{\partial V_{SS}} \right\rvert} = A_{vd}$	5.34×10^{3} $(74.6dB)$	5.38×10^{3} $(74.6dB)$

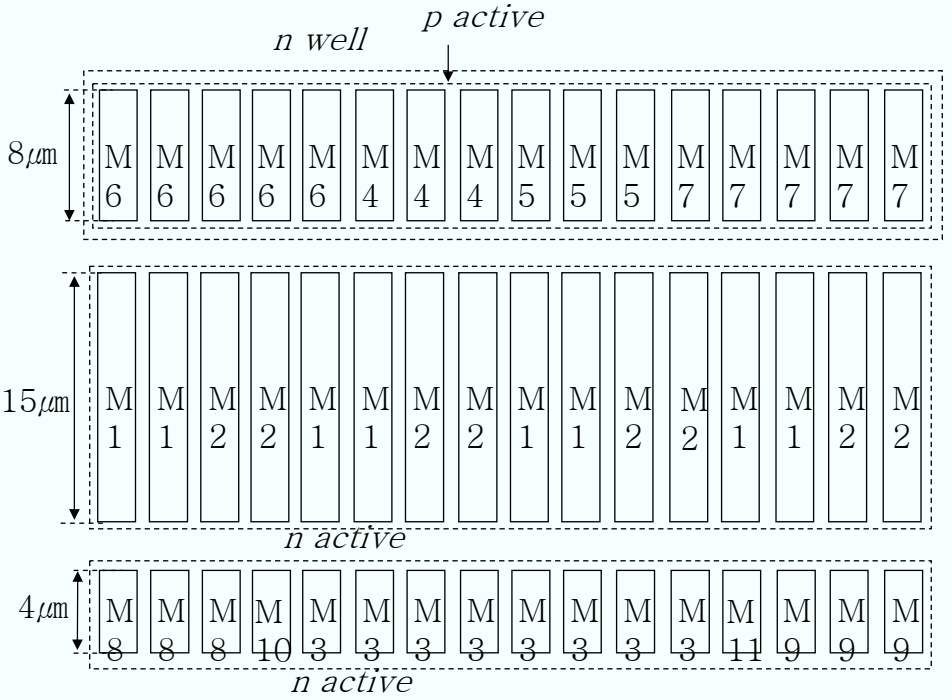
SPICE simulation: Folded cascode OP amp

표 9.2.1 OP amp 의 주파수 특성 관련 파라미터들(부하 커패시터 $C_L = 10pF$)

	식	계산 값	SPICE
Dominant pole freq. [Hz] $\left(\lvert p_1 \rvert / 2\pi\right)$	$\frac{1}{2\pi} \cdot \frac{1}{R_o C_L}$	3.8KHz	3.7 KHz
non-dominant pole freq. $\left(\lvert p_2 \rvert / 2\pi\right)$ [Hz]	$\frac{1}{2\pi \cdot r_{s6} \cdot \left[\begin{array}{l} C_{GS6} + C_{GSOV6} + C_{BS6} \\ + C_{GDOV1} \cdot \left(1 + \frac{g_{m6}}{g_{m1}}\right) \\ + C_{BD1} + C_{GDOV4} + C_{BD4} \end{array}\right]}$	478 MHz	336 MHz
Gain-bandwidth 곱 $(\omega_T / 2\pi)$ [Hz]	$\frac{1}{2\pi} \cdot \frac{g_{m1}}{C_L}$	20.4 MHz	19.7 MHz
phase margin at unity-gain 피드백	$90^\circ - \tan^{-1}\left\lvert \frac{\omega_{0dB}}{p_2} \right\rvert$	88°	87°

Layout : Folded cascode OP amp





Layout : Folded cascode OP amp