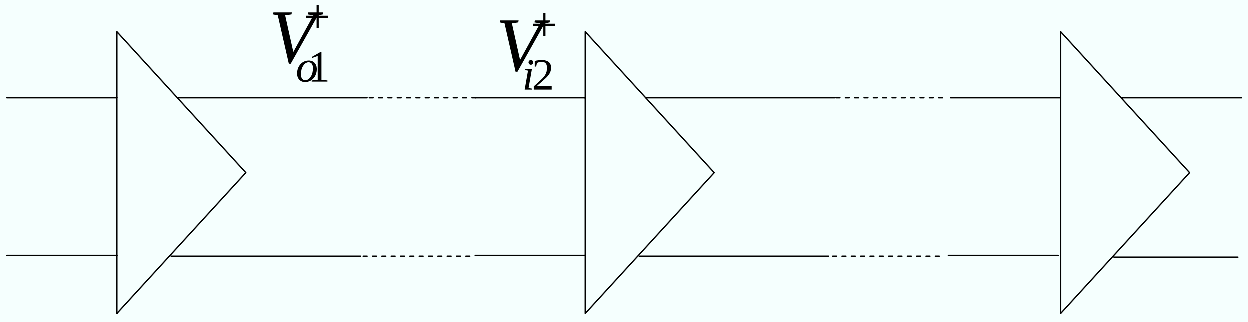
CH10 Common mode feedback and fully differential OP amp

10.1 Common mode feedback (CMFB)

10.2 Fully differential OP amp

Fully differential OP amp

Differential input, Differential output
➔ Easy to cascade OP amps
➔ insensitive to supply noise
➔ High gain Fully diff OP amp requires CMFB

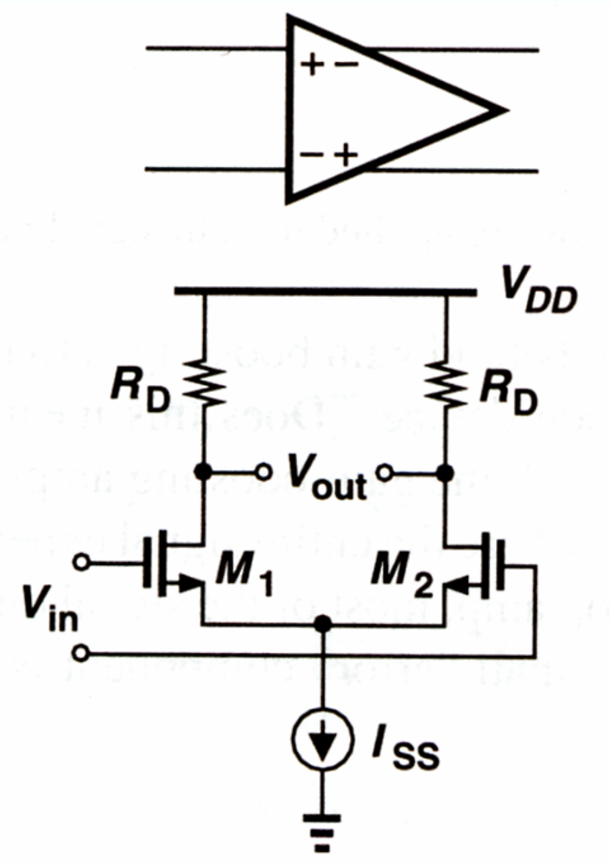


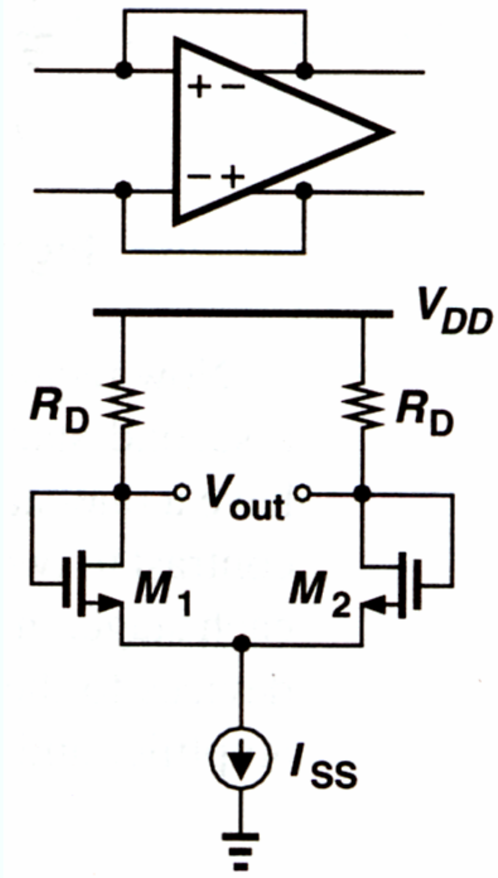
Common mode feedback (CMFB)

Low-gain fully differential OP amp:

➔ VoutCM common mode output voltage = VDD-0.5 RD x ISS (well defined)

➔ CMFB ckt not required





VoutCM : determined by unity-gain FB

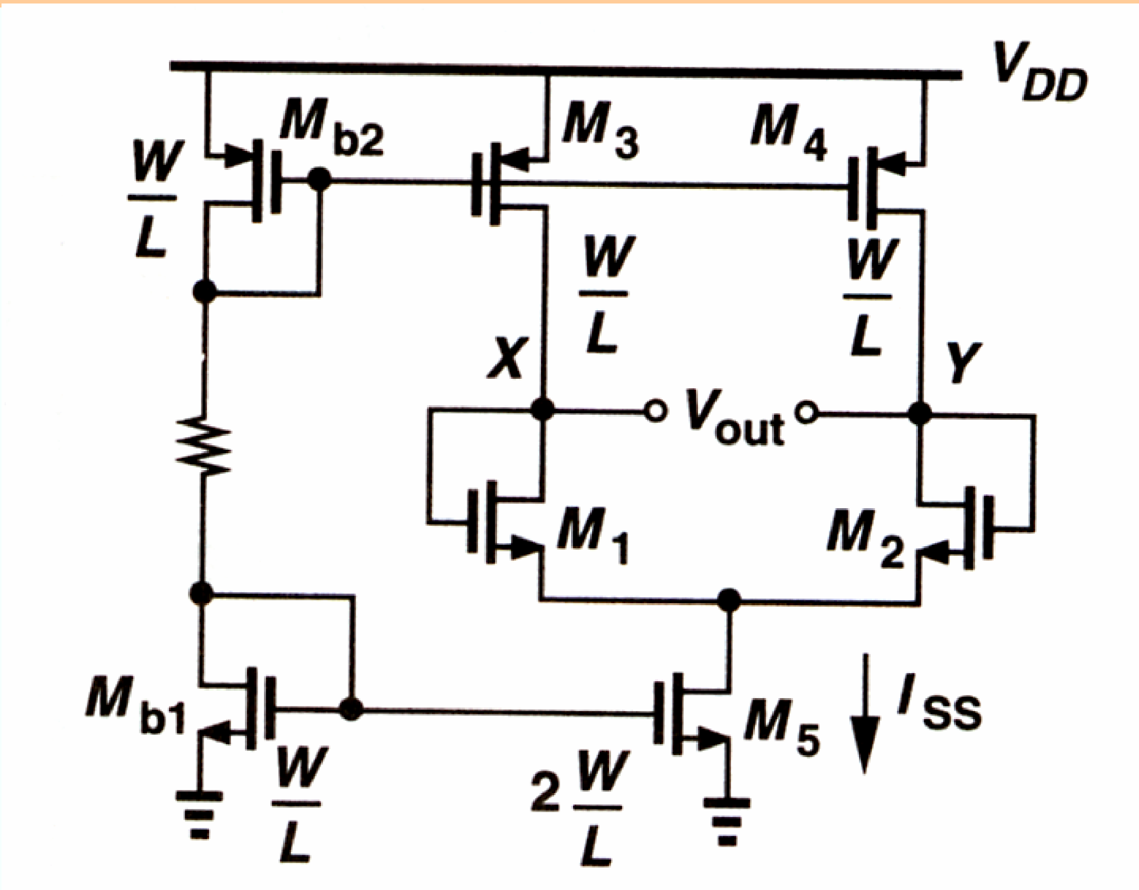
Razavi

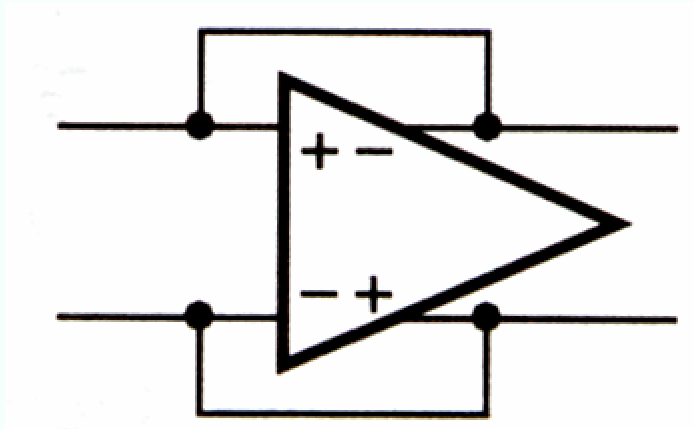
Common mode feedback (CMFB)

High-gain fully differential OP amp:

➔ VoutCM : function of device parameters : Not well defined
(if ID3 > 0.5 ISS, M3 M4 triode, VoutCM: close to VDD,
if ID3 < 0.5 ISS, M5 triode, VoutCM: close to VSS) ➔ very low diff gain

➔ CMFB ckt required



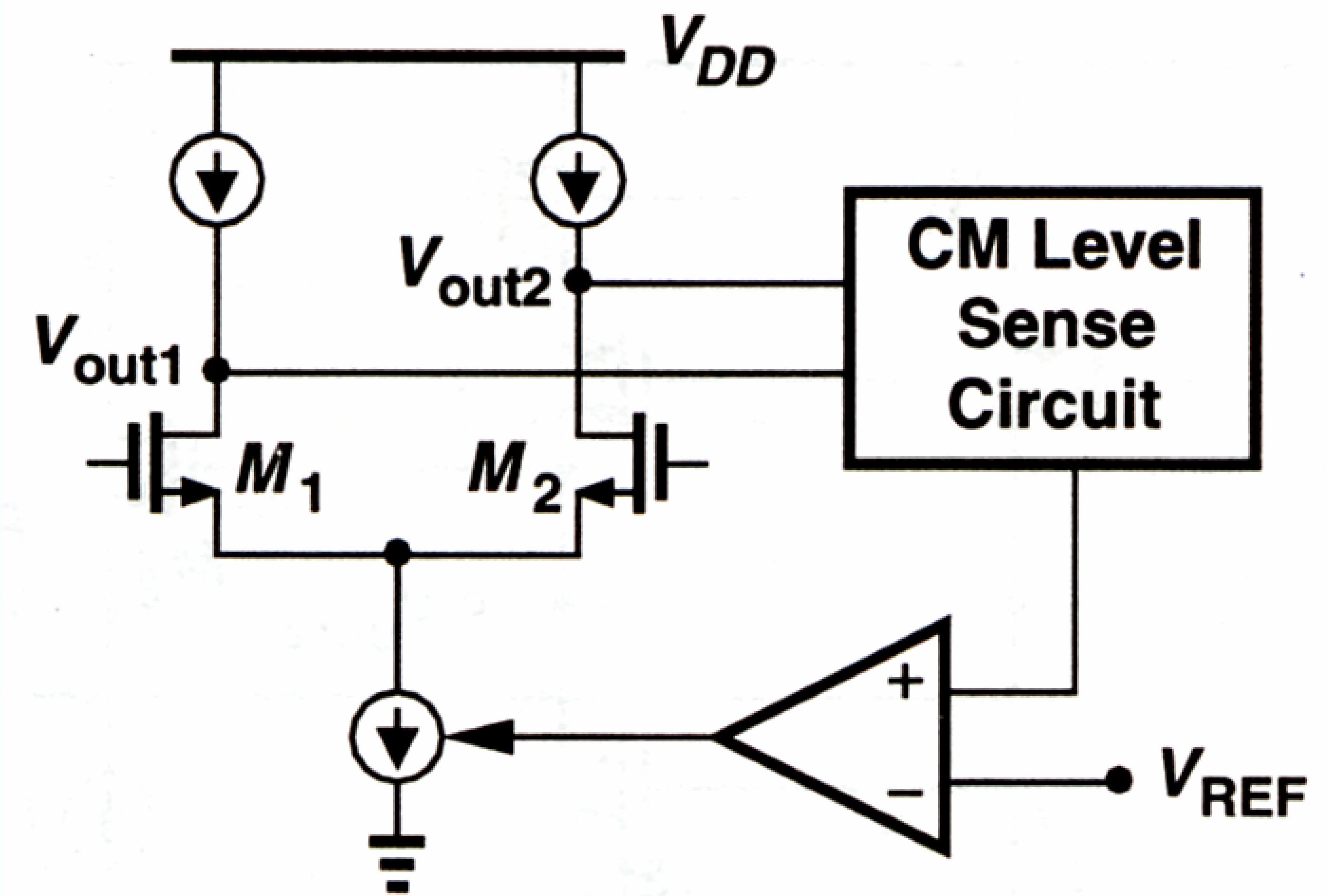


Differential unity-gain FB

Razavi

Common mode feedback (CMFB)

VoutCM : well defined
➔ all TR in saturation region ➔ high diff gain



Only a part of current sources can be driven by CMFB circuit

Razavi

CMFB circuits

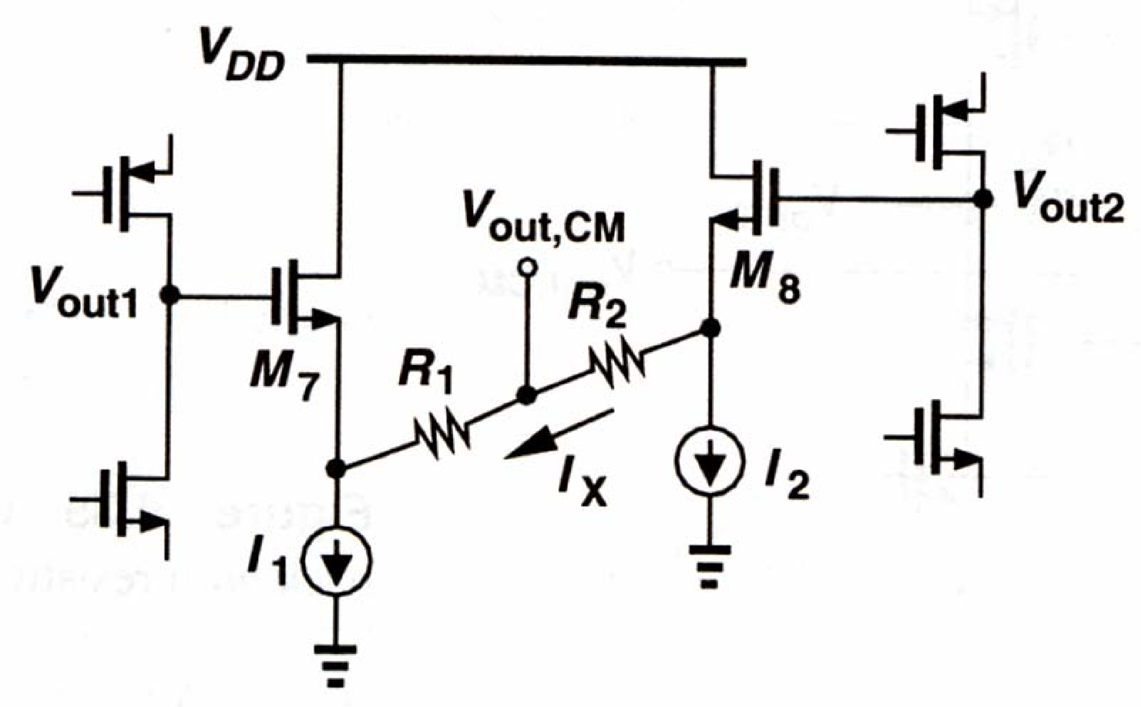
(1) Source follower + resistor divider CMFB ckt

(2) Triode TR CMFB ckt

(3) Diff pair CMFB ckt

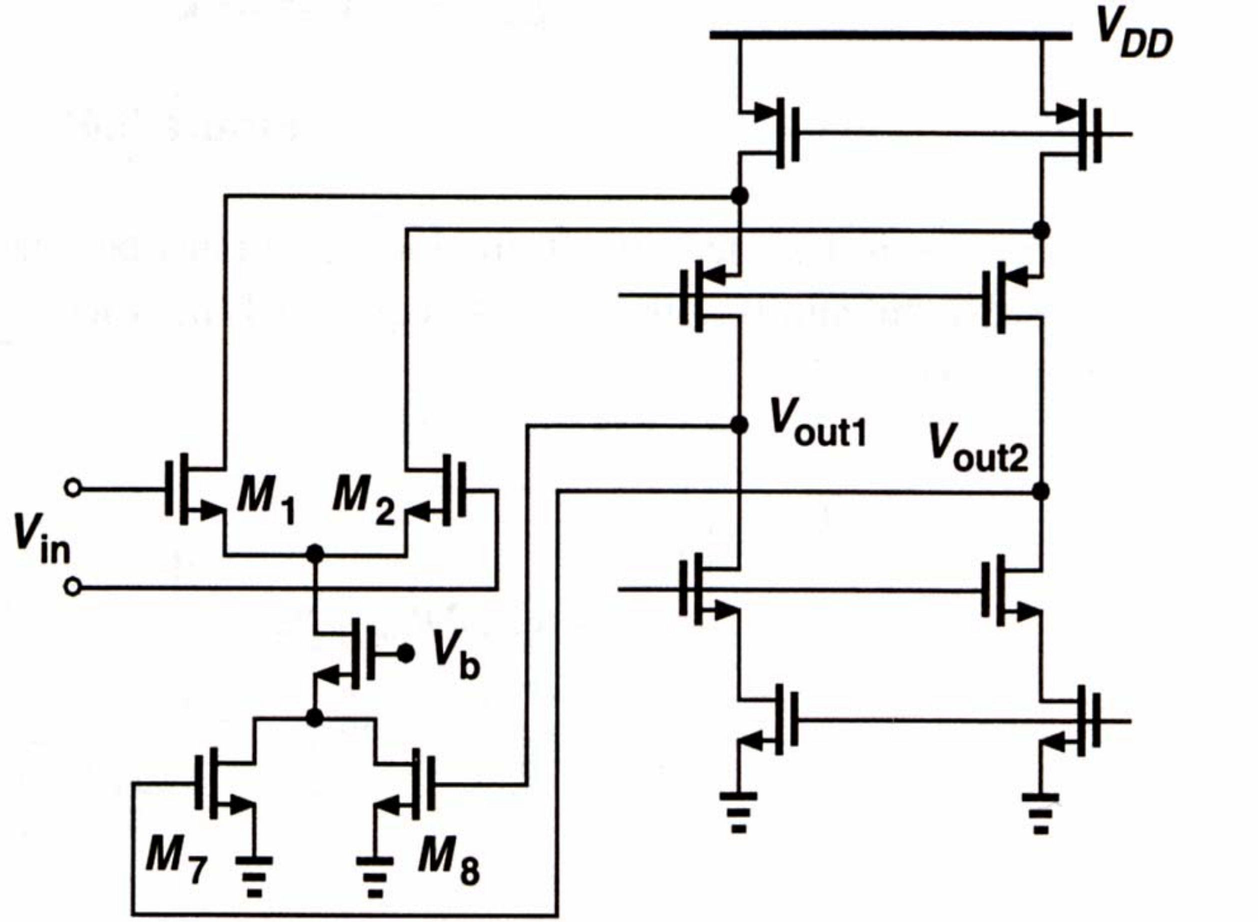
(4) Switched-capacitor CMFB ckt

(1) Source follower + resistor divider CMFB ckt



Vout MIN limited to VGS7 + V(I1)
I1 x (R1 + R2) > Vout swing ➔ large I1 or large R1, R2
Usually W/L (M7, M8) very large

(2) Triode TR CMFB ckt

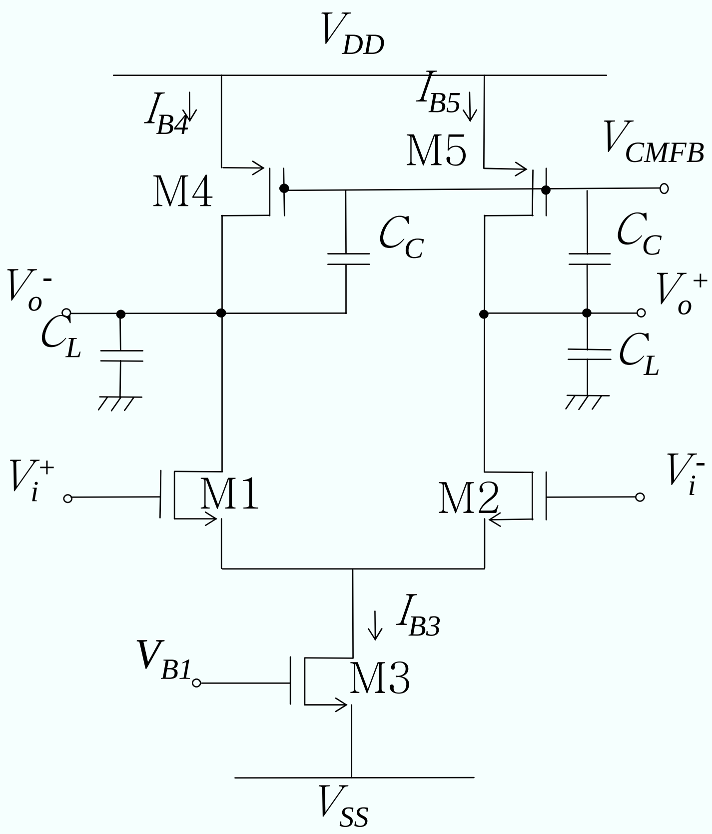


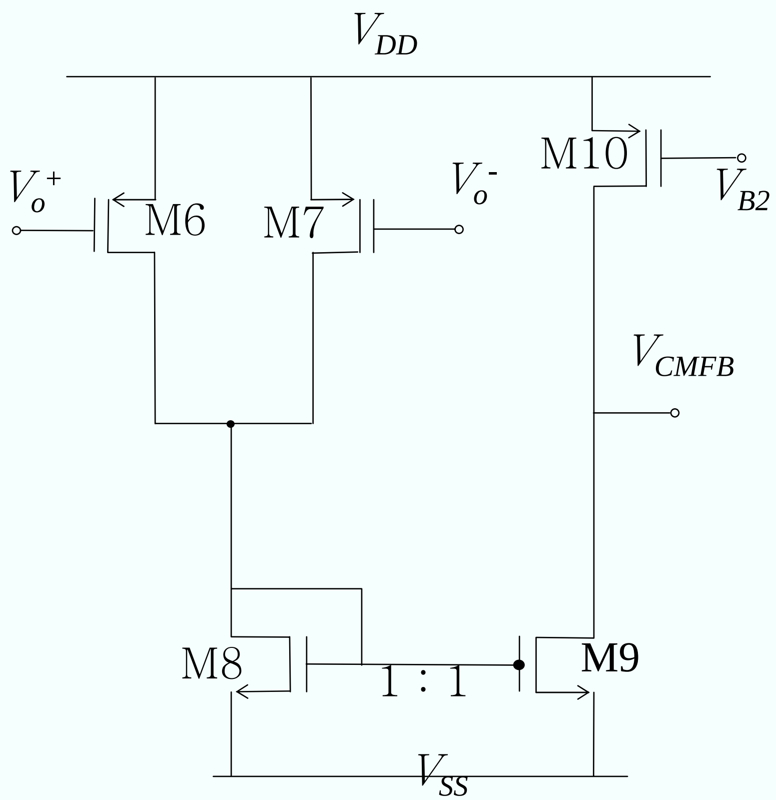
Vout MIN limited to VTHn
M7, M8: deep triode, large W/L ➔ large cap

M7, M8: not in the signal path
➔ large cap no effect in diff gain

Razavi

(3) Diff pair CMFB circuit 1

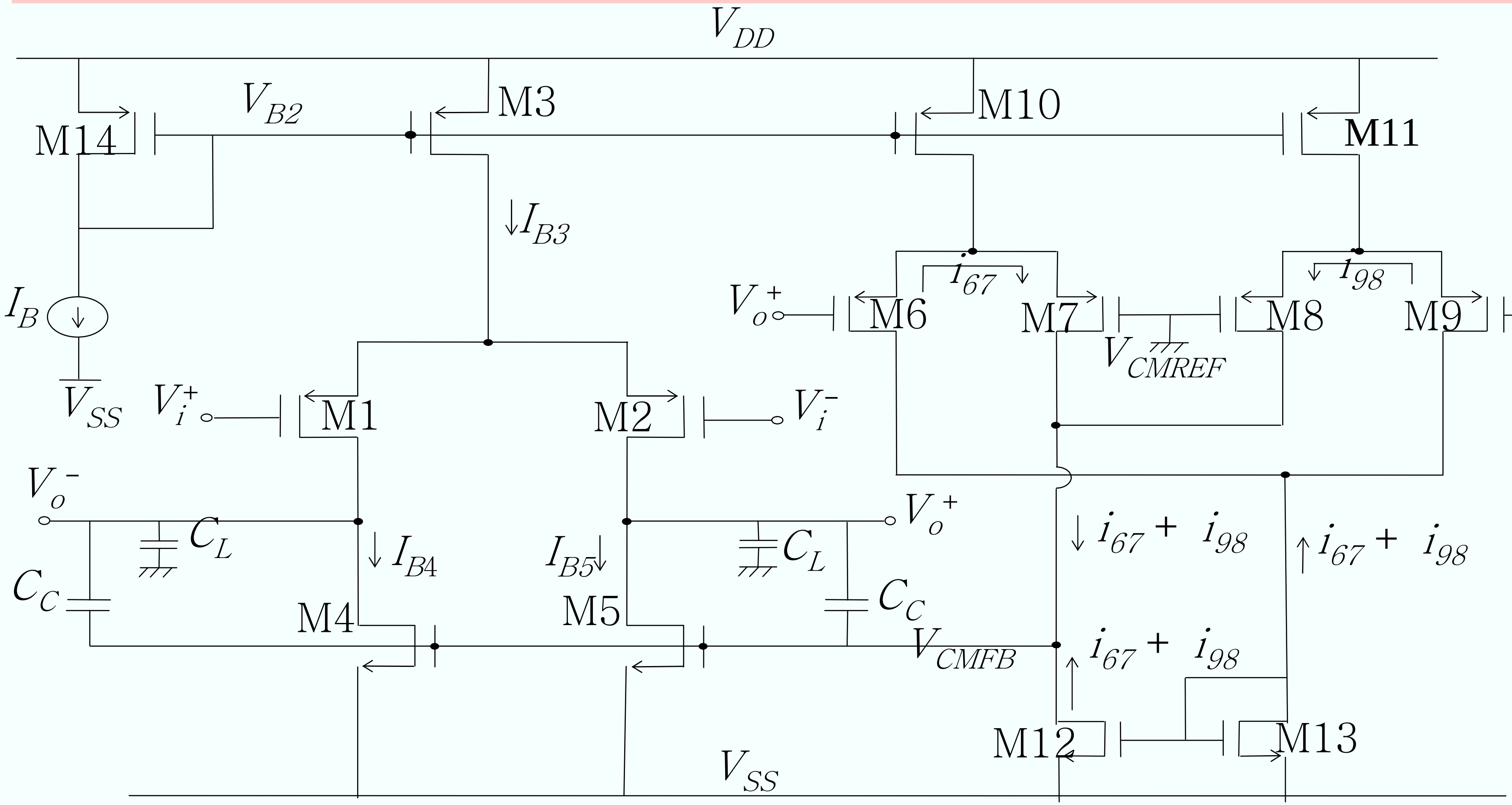




Fully Diff OP amp
Vout MAX limited to VDD – |VTHp|
2-stage CM amp ➔ needs freq compensation

CMFB circuit :
Vcmfb=A x 0.5(Vo+ + Vo–)
W/L(M6,M7) very small to increase
linear operating range

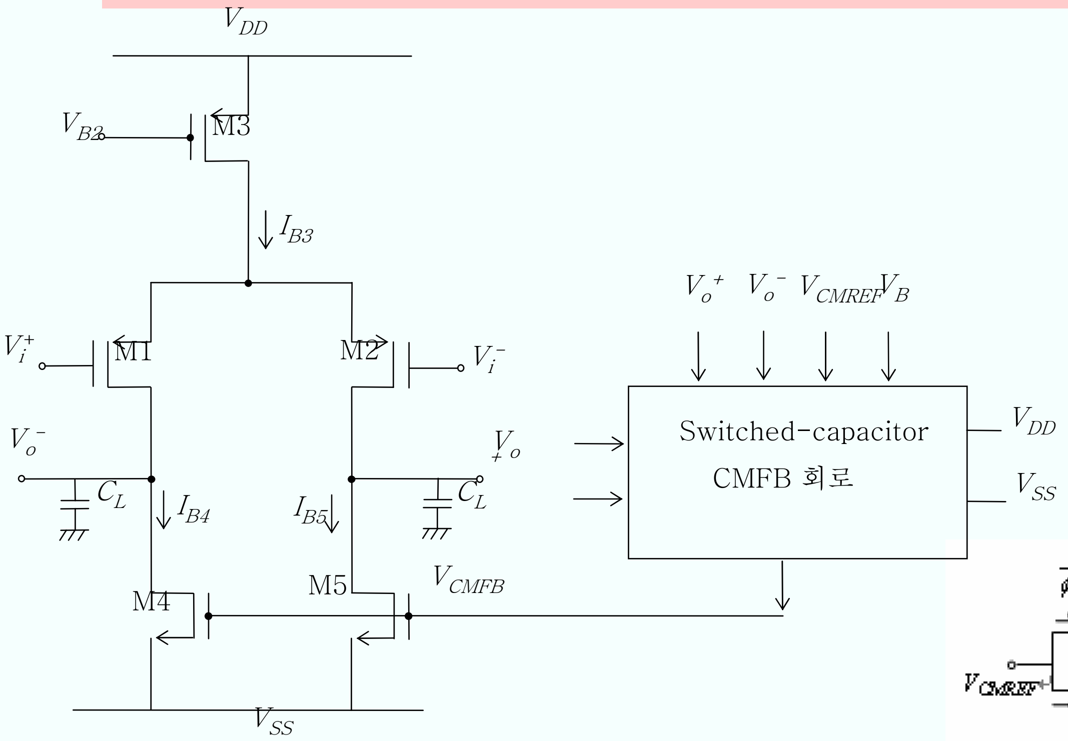
(3) Diff pair CMFB circuit 2



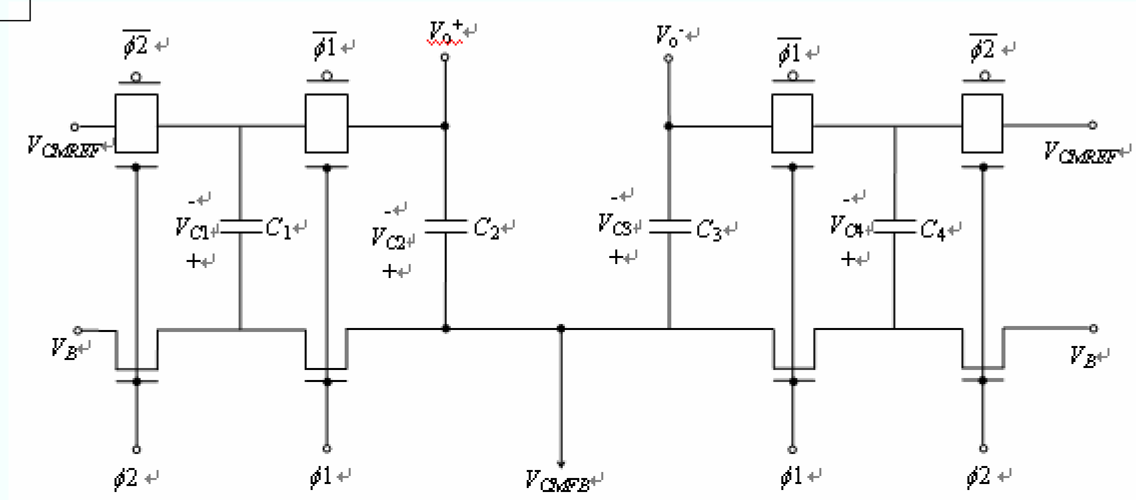
Vout MAX limted to VDD – VDSAT10 – |VGS6|, VoutCM set to VcmREF
W/L(M6,M7,M8,M9) very small to increase linear operating range of CMFB circuit

Common mode feedback (CMFB)

(4) Switched-capacitor CMFB ckt



$$V_{CMFB} = V_B + \left(\frac{V_o^+ + V_o^-}{2} - V_{CMREF} \right)$$



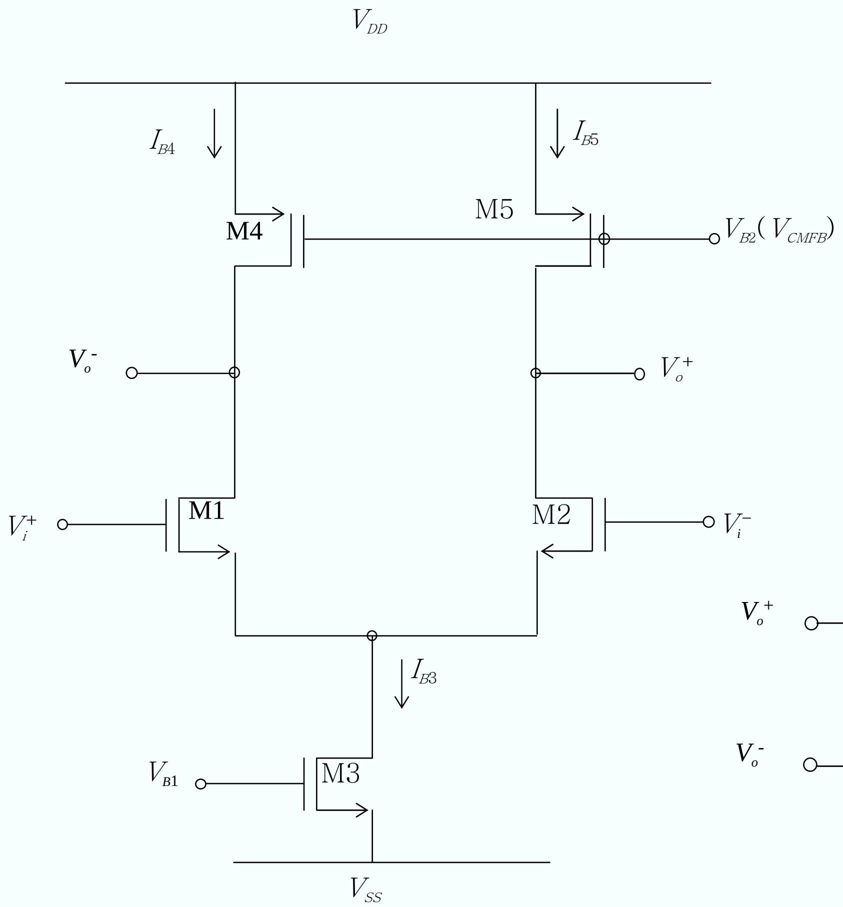
Can be used in switching circuits
No limit in Vout

10.1.1 Function of CMFB circuit

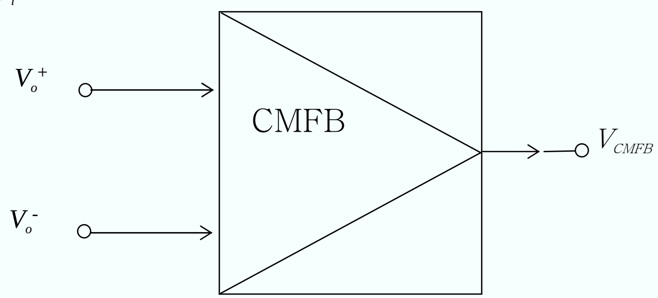
$$\frac{\partial V_o^+}{\partial V_{B1}} = \frac{\partial V_o^-}{\partial V_{B1}} = \frac{1}{2} \cdot g_{m3} \cdot \left\{ r_{o4} \parallel (g_{m1} r_{o1} \cdot 2 r_{o3}) \right\}$$

$$\frac{\partial V_o^+}{\partial V_{B2}} = \frac{\partial V_o^-}{\partial V_{B2}} = g_{m4} \cdot r_{o4} \parallel (g_{m1} r_{o1} \cdot 2 r_{o3})$$

Apply a negative FB on CM signal



(a)



(b)

Fig. 10.1.2 (a) Simple fully differential CMOS OP amp circuit
(b) CMFB(common mode feedback) circuit

10.1.2 CMFB circuit 1 using MOS diff amp (*)

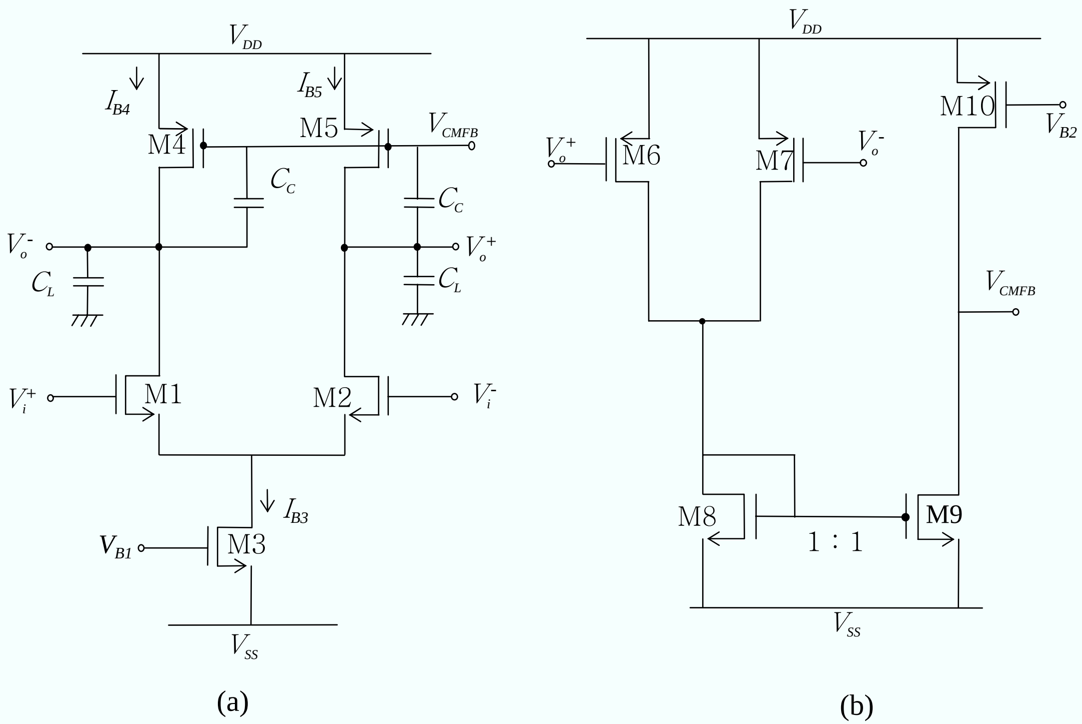


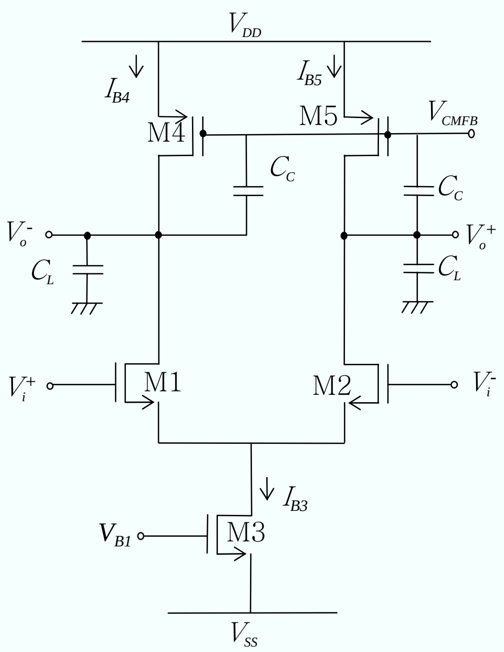
Fig10.1.3 CMFB circuit 1 using MOS diff amp (a) OP amp (b) CMFB circuit

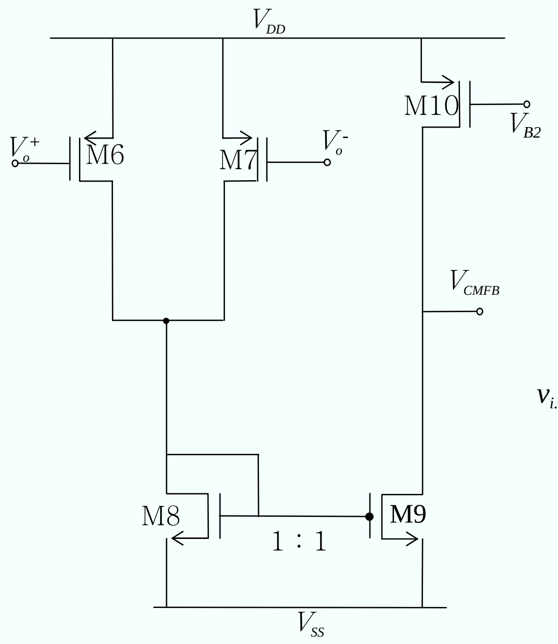
$$v_{CMFB} = + g_{m6} \cdot (r_{o9} \| r_{o10}) \cdot (v_o^+ + v_o^-)$$

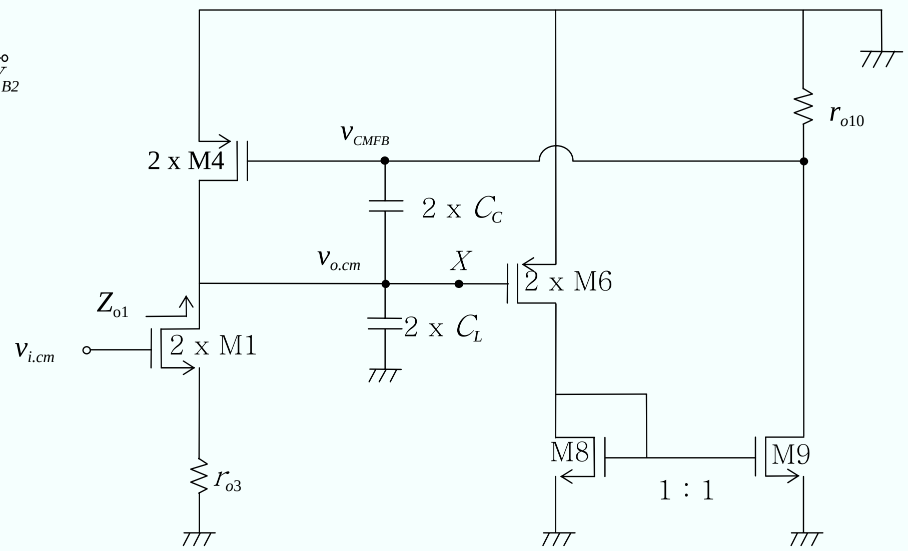
No reference for VoutCM

CMFB circuit 1 using MOS diff amp

Small-signal common mode voltage gain







$$(CMFB\ \text{loop gain}) = \frac{2g_{m6}\cdot(r_{o9}\parallel r_{o10})\cdot(g_{m4}\cdot r_{o4})}{1+s\cdot(r_{o9}\parallel r_{o10})\cdot(g_{m4}\cdot r_{o4})\cdot(2C_c)}$$

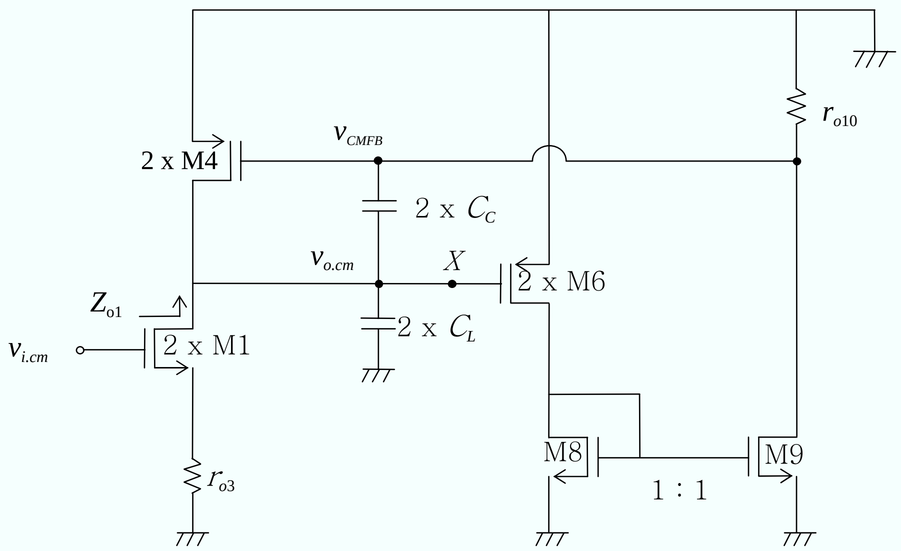
$$g_{m1}r_{o1}\cdot r_{o3} >> 0.5\cdot r_{o4}$$

$$\omega_{T.CMFB} = \frac{g_{m6}}{C_C}$$

CMFB circuit 1 using MOS diff amp

$$Z_{o1}(s) = \frac{\frac{r_{o4}}{2}}{\left\{1 + s\cdot\frac{r_{o4}}{2}\cdot(2C_L + 2C_C)\right\}\cdot\{1 + (CMFB\ loop\ gain)\}}$$

$$\approx \frac{1}{4\cdot g_{m6}\cdot(r_{o9}\parallel r_{o10})\cdot g_{m4}}\cdot\frac{1 + s\cdot(r_{o9}\parallel r_{o10})\cdot(g_{m4}r_{o4})\cdot 2C_C}{1 + s\cdot r_{o4}\cdot(C_L + C_C)}$$



$$A_{vc}(s) = -\frac{Z_{o1}(s)}{\frac{r_{s1}}{2} + r_{o3}} \approx -\frac{Z_{o1}(s)}{r_{o3}}$$

$$= -\frac{1}{4\cdot g_{m6}\cdot(r_{o9}\parallel r_{o10})\cdot(g_{m4}r_{o3})}\cdot\frac{1 + s\cdot(r_{o9}\parallel r_{o10})\cdot(g_{m4}r_{o4})\cdot 2C_C}{1 + s\cdot r_{o4}\cdot(C_L + C_C)}$$

CMFB circuit 1 using MOS diff amp

Small-signal differential mode voltage gain

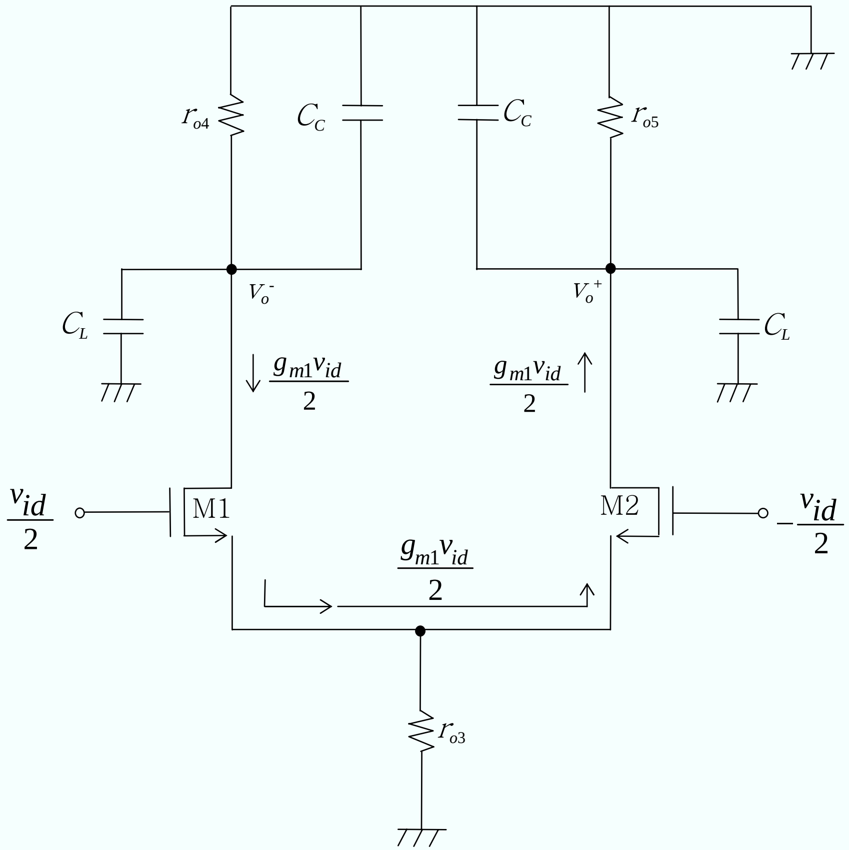
$$i_x = \frac{v_x}{r_{o4}+r_{o5}} + \frac{v_x}{2r_{o1}} = \frac{v_x}{2r_{o4}} + \frac{v_x}{2r_{o1}} = \frac{v_x}{2\cdot(r_{o1} \parallel r_{o4})}$$

$$R_o = 2\cdot(r_{o1} \parallel r_{o4})$$

$$A_{vd} \triangleq \frac{v_o^+ - v_o^-}{v_i^+ - v_i^-} = \frac{g_{m1}\cdot(r_{o1} \parallel r_{o4})}{1+s\cdot(r_{o1} \parallel r_{o4})\cdot(C_L + C_C)}$$

$$\omega_{T.dm} = \frac{g_{m1}}{C_C + C_L}$$

$$\omega_{T.CMFB} = \frac{g_{m6}}{C_C}$$



CMFB circuit 1 using MOS diff amp

$$A_{vd} \triangleq \frac{v_o^+ - v_o^-}{v_i^+ - v_i^-} = \frac{g_{m1} \cdot (r_{o1} \| r_{o4})}{1 + s \cdot (r_{o1} \| r_{o4}) \cdot (C_L + C_C)}$$

$$\omega_{T.dm} = \frac{g_{m1}}{C_C + C_L}$$

$$(CMFB \text{ loop gain}) = \frac{2 g_{m6} \cdot (r_{o9} \| r_{o10}) \cdot (g_{m4} \cdot r_{o4})}{1 + s \cdot (r_{o9} \| r_{o10}) \cdot (g_{m4} \cdot r_{o4}) \cdot (2C_c)}$$

$$\omega_{T.CMFB} = \frac{g_{m6}}{C_C}$$

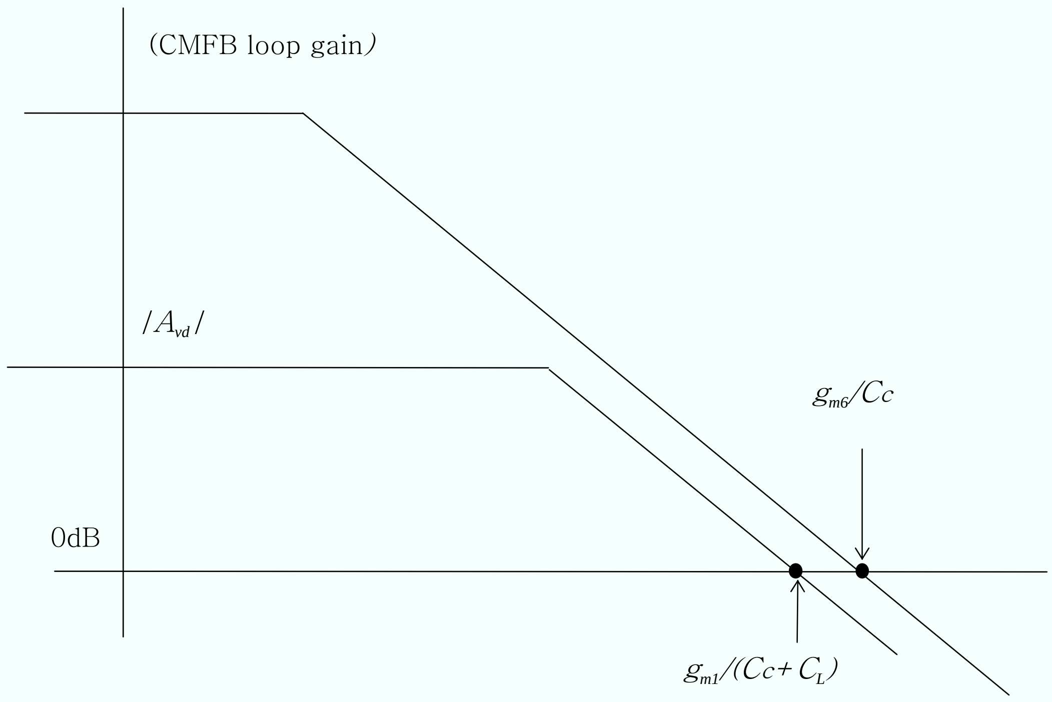


Fig 10.1.6 Bode plot of CMFB loop gain of Fig.10.1.3 circuit

CMFB circuit 1 using MOS diff amp

Linear range of differential mode output voltage

Min : $V_{SS} + V_{DSAT\,8} + V_{THn} - |V_{THp}| \approx V_{SS} + V_{DSAT\,8}$

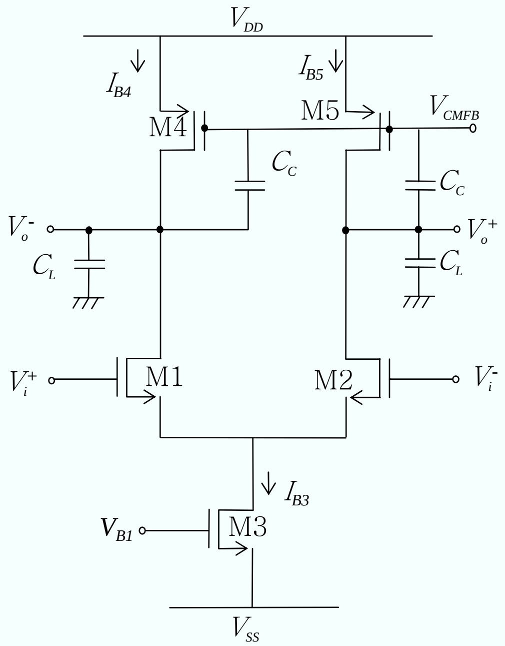
Max : $V_{DD} - |V_{THp}| - |V_{DSAT\,6}|$

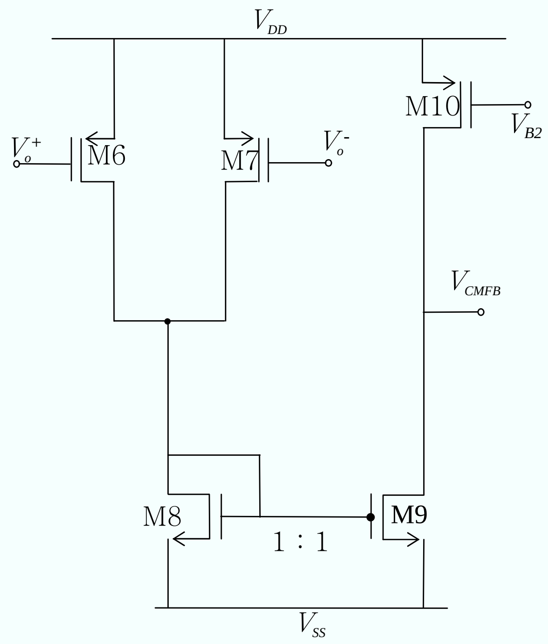
Severely limited because of large Vdsat6

$$g_{m6} = 2 \cdot I_{D6} \Big/ |V_{GS\,6} - V_{THp}|$$

$$V_{CMFB.\max} = V_{B2} + |V_{THp}|$$

To increase the linear operating range of CMFB circuit
➔ VGS6-VTH increased
➔ gm6 decreased
➔ low CMFB loop gain



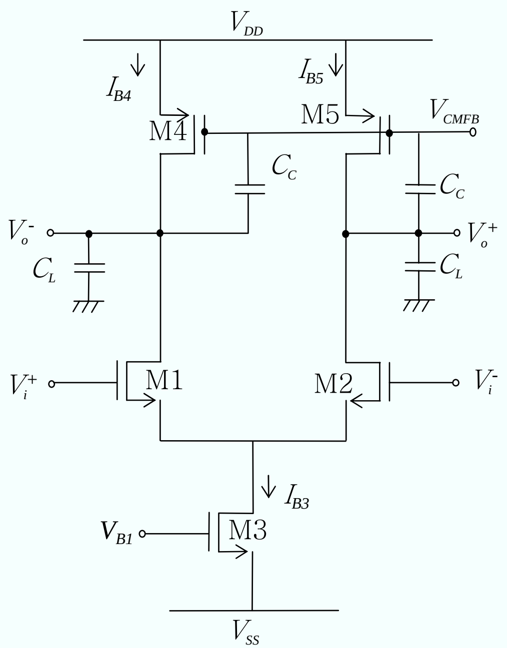


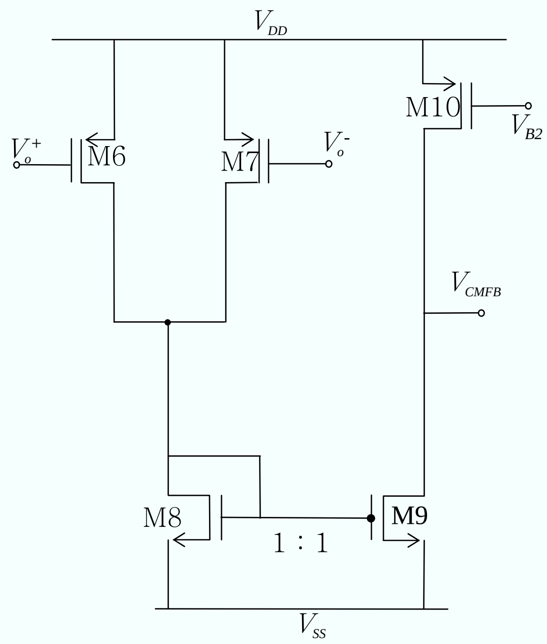
CMFB circuit 1 using MOS diff amp

Active input common mode voltage range

Max: $$V_{CMFB\max} + |V_{THp}| + V_{THn} = V_{B2} + 2\cdot|V_{THp}| + V_{THn}$$

Min : $$V_{SS} + V_{DSAT3} + V_{DSAT1} + V_{THn} \approx V_{B1} + V_{DSAT1}$$ limited





10.1.3 CMFB circuit using a triode TR feedback

$$g_{m6} = \mu_p C_{ox} \cdot \left(\frac{W}{L}\right)_6 \cdot |V_{DS}|$$

M6, M7 deep triode
➔ No gain stage
➔ No freq comp.

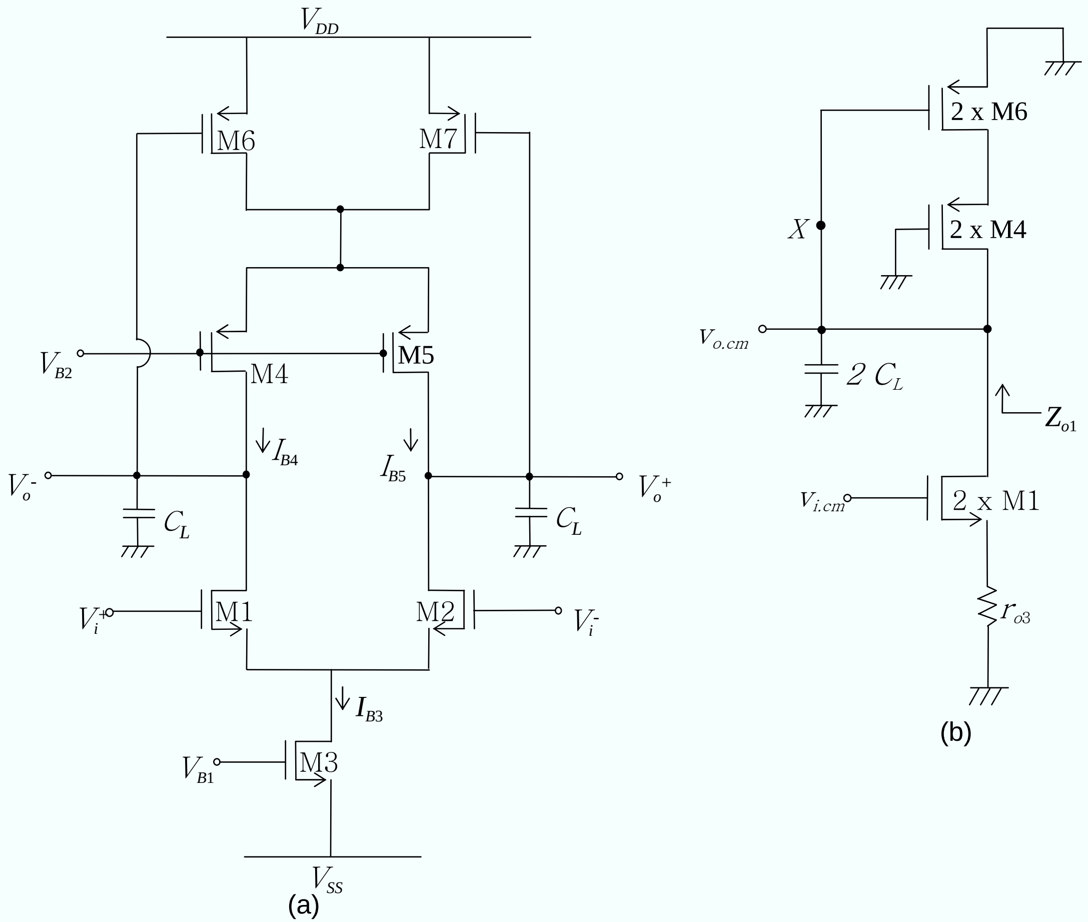


Fig 10.1.7 (a) Fully differential CMOS OP amp using a triode TR feedback
(b) Small-signal equivalent circuit of (a) circuit

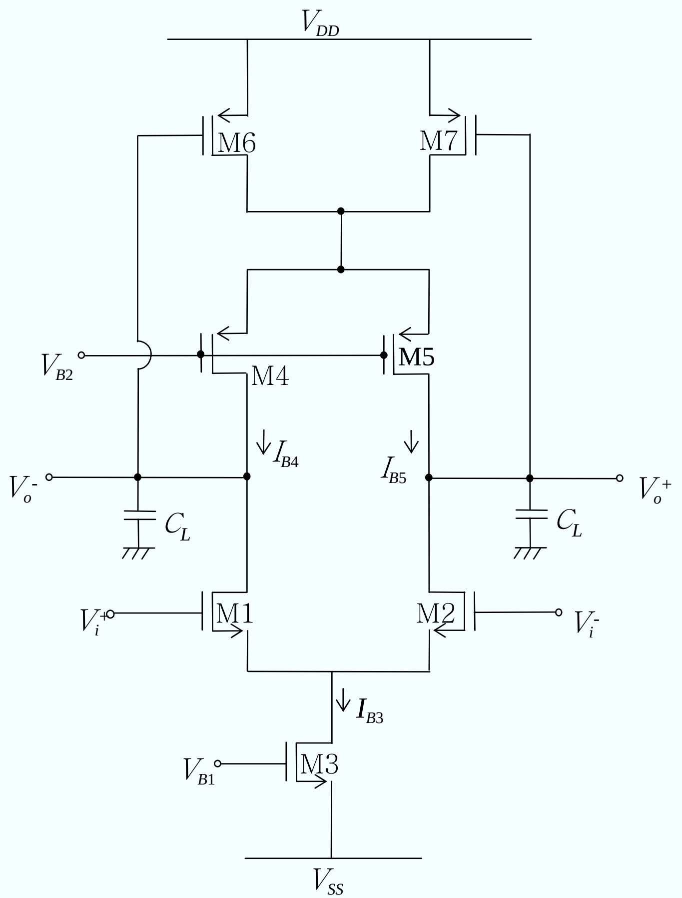
CMFB circuit using a triode TR feedback

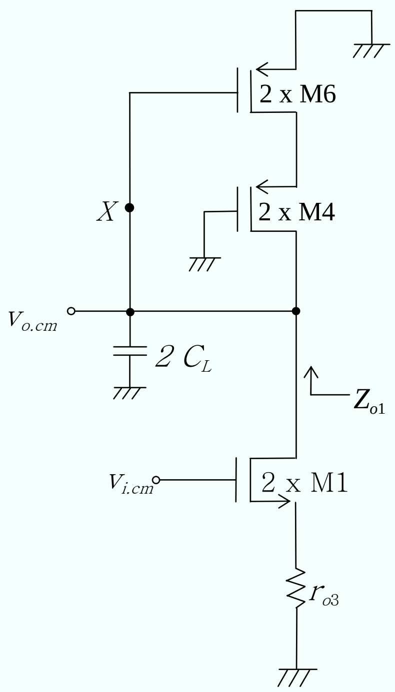
(*CMFB* loop gain)

$$= 2g_{m6} \cdot \frac{\frac{r_{o6}}{2}}{\frac{r_{s4}}{2} + \frac{r_{o6}}{2}} \cdot R_o \cdot \frac{1}{1 + s \cdot R_o \cdot 2C_L} = 2 \cdot g_{m6} R_o \cdot \frac{r_{o6}}{r_{s4} + r_{o6}} \cdot \frac{1}{1 + s \cdot R_o \cdot 2C_L}$$

$$R_o = \left(2g_{m1} \cdot \frac{r_{o1}}{2} \cdot r_{o3}\right) \Bigg\| \left(2g_{m4} \cdot \frac{r_{o4}}{2} \cdot \frac{r_{o6}}{2}\right) = \left(g_{m1} r_{o1} \cdot r_{o3}\right) \Bigg\| \left\{\frac{g_{m4} r_{o4} \cdot r_{o6}}{2}\right\} \approx \frac{g_{m4} r_{o4} \cdot r_{o6}}{2}$$

$GBW(CMFB) =$ $\dfrac{g_{m6}}{C_L} \cdot \dfrac{r_{o6}}{r_{s4} + r_{o6}}$





CMFB circuit using a triode TR feedback

Small-signal common mode voltage gain

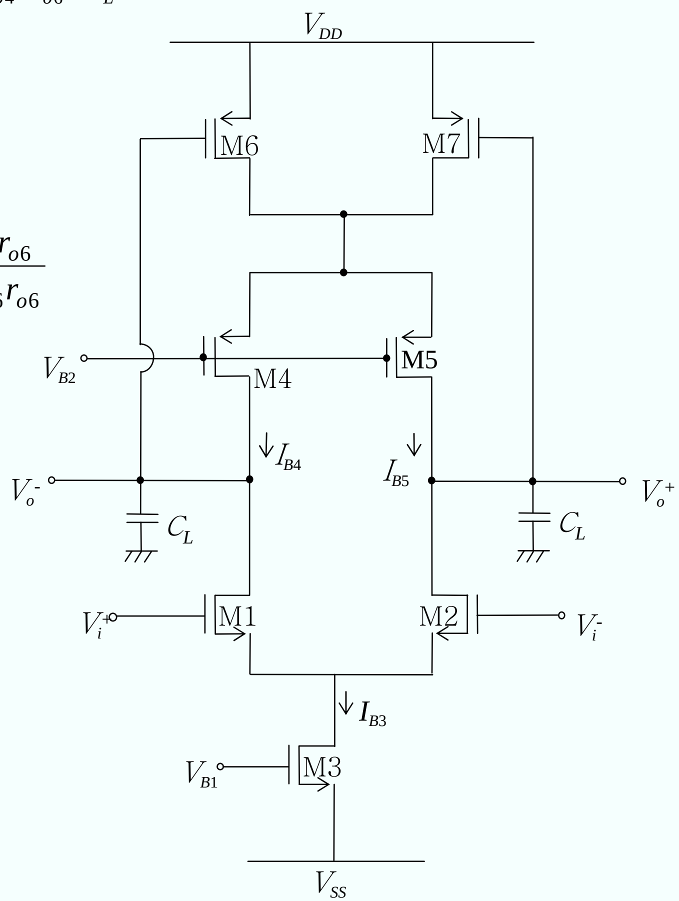
$$A_{vc}(s) \triangleq \frac{v_{o.cm}}{v_{i.cm}} = -\frac{Z_{o1}(s)}{\frac{r_{s1}}{2}+r_{o3}} \approx -\frac{Z_{o1}(s)}{r_{o3}}$$

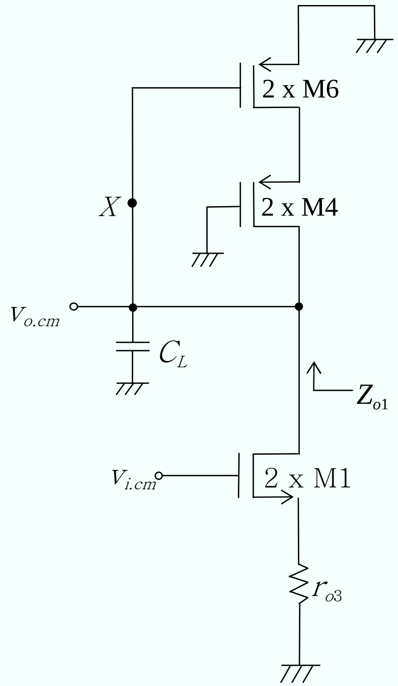
$$\left(2g_{m4}\cdot\frac{r_{o4}}{2}\cdot\frac{r_{o6}}{2}\right)\|\frac{1}{s\cdot 2C_L} = (0.5\cdot g_{m4}r_{o4}\cdot r_{o6})\|\frac{1}{s\cdot 2C_L} = \frac{0.5\cdot g_{m4}r_{o4}\cdot r_{o6}}{1+s\cdot g_{m4}r_{o4}\cdot r_{o6}\cdot C_L}$$

$$Z_{o1}(s) = \frac{0.5\cdot g_{m4}r_{o4}\cdot r_{o6}}{1+s\cdot g_{m4}r_{o4}\cdot r_{o6}\cdot C_L}\cdot\frac{1}{1+(CMFB\ loop\ gain)}$$

$$\approx \frac{0.5\cdot g_{m4}r_{o4}\cdot r_{o6}}{1+s\cdot g_{m4}r_{o4}\cdot r_{o6}\cdot C_L}\cdot\frac{1}{(CMFB\ loop\ gain)} \qquad = \frac{r_{s4}+r_{o6}}{2\cdot g_{m6}r_{o6}}$$

$$A_{vc}(s) = -\frac{1}{2\cdot g_{m6}r_{o3}}\cdot\frac{r_{s4}+r_{o6}}{r_{o6}}$$



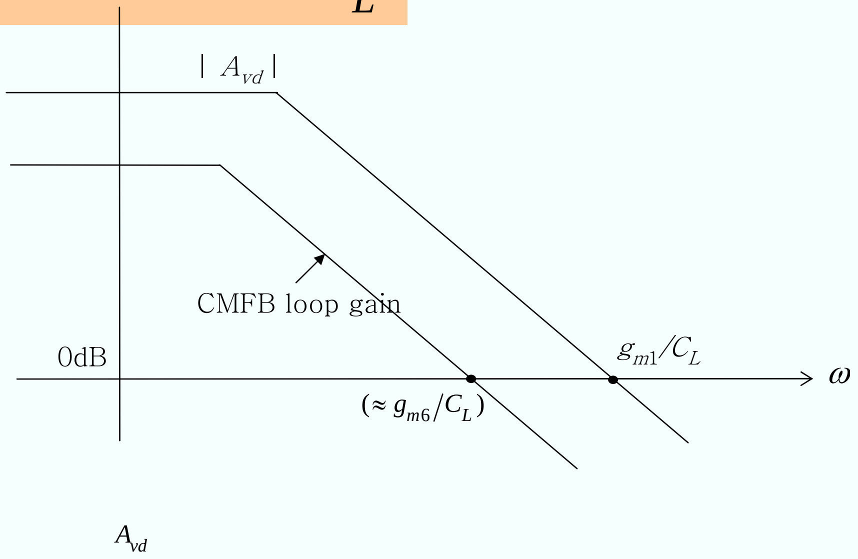


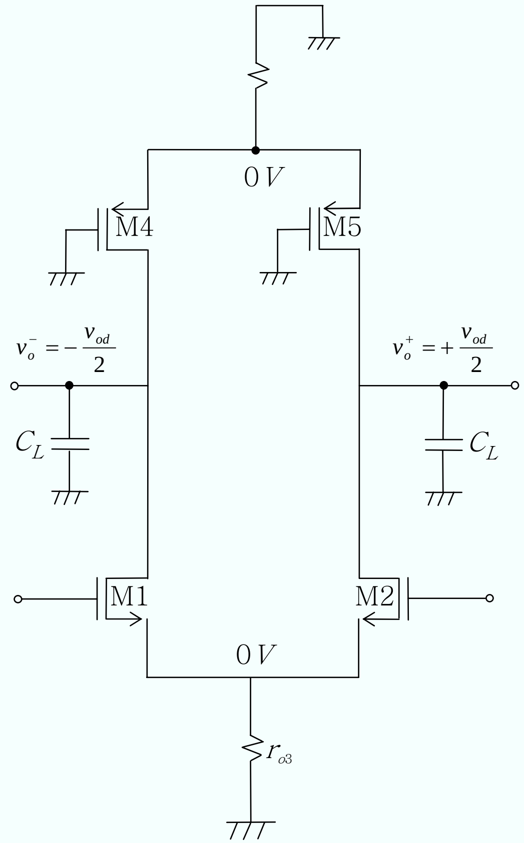
CMFB circuit using a triode TR feedback

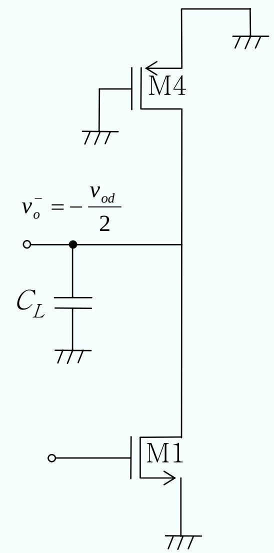
Small-signal differential mode voltage gain

$$A_{vd}(s) \triangleq \frac{v_{od}}{v_{id}} = \frac{g_{m1}\cdot(r_{o1}\,\|\,r_{o4})}{1+s\cdot(r_{o1}\,\|\,r_{o4})\cdot C_L}$$

$$GBW(A_{vd}) = \frac{g_{m1}}{C_L}$$





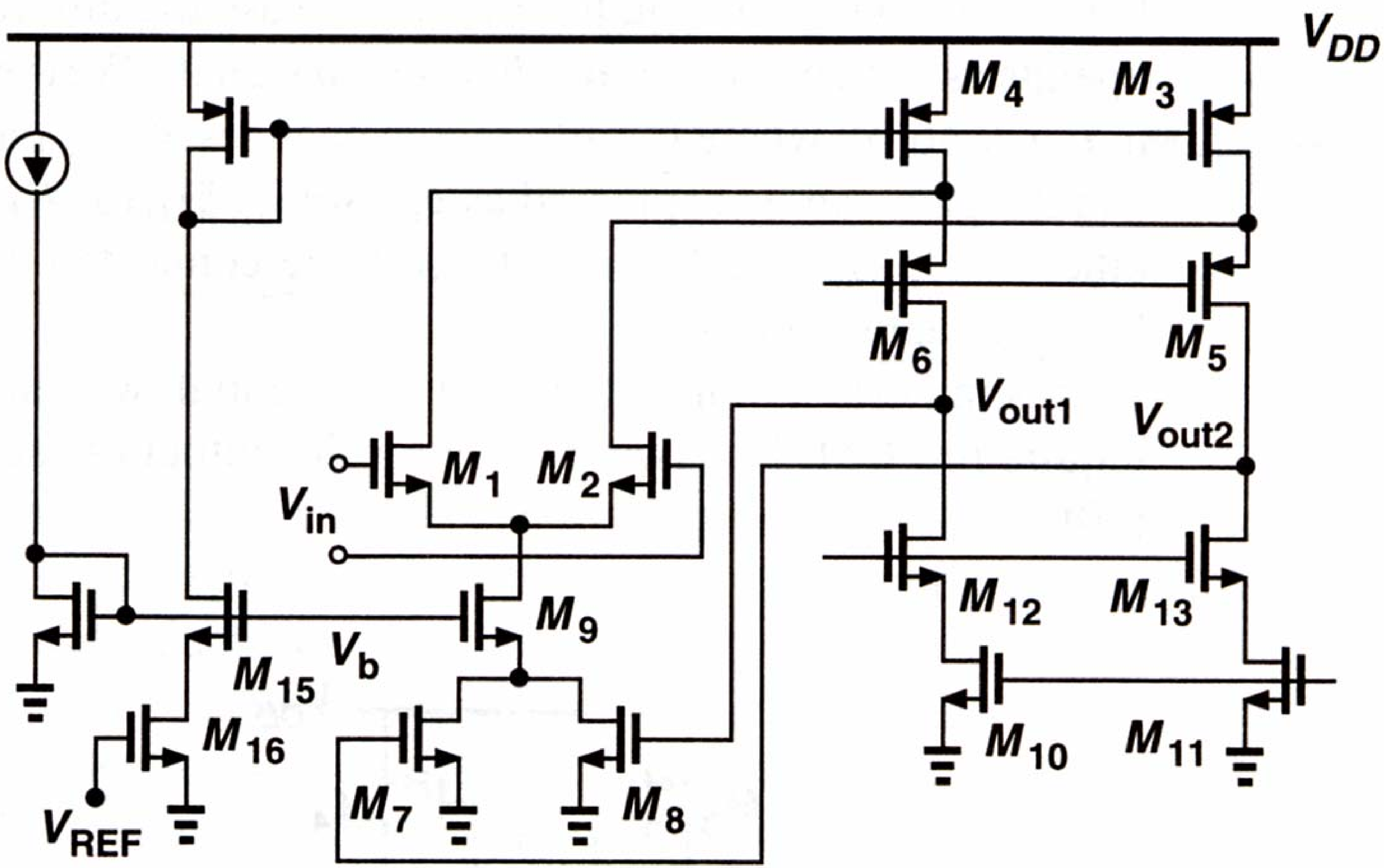


$$g_{m1} = \mu_n C_{ox}\cdot\left(\frac{W}{L}\right)_1\cdot(V_{GS1}-V_{THn})$$

$$g_{m6} = \mu_p C_{ox}\cdot\left(\frac{W}{L}\right)_6\cdot|V_{DS6}|$$

Triode region

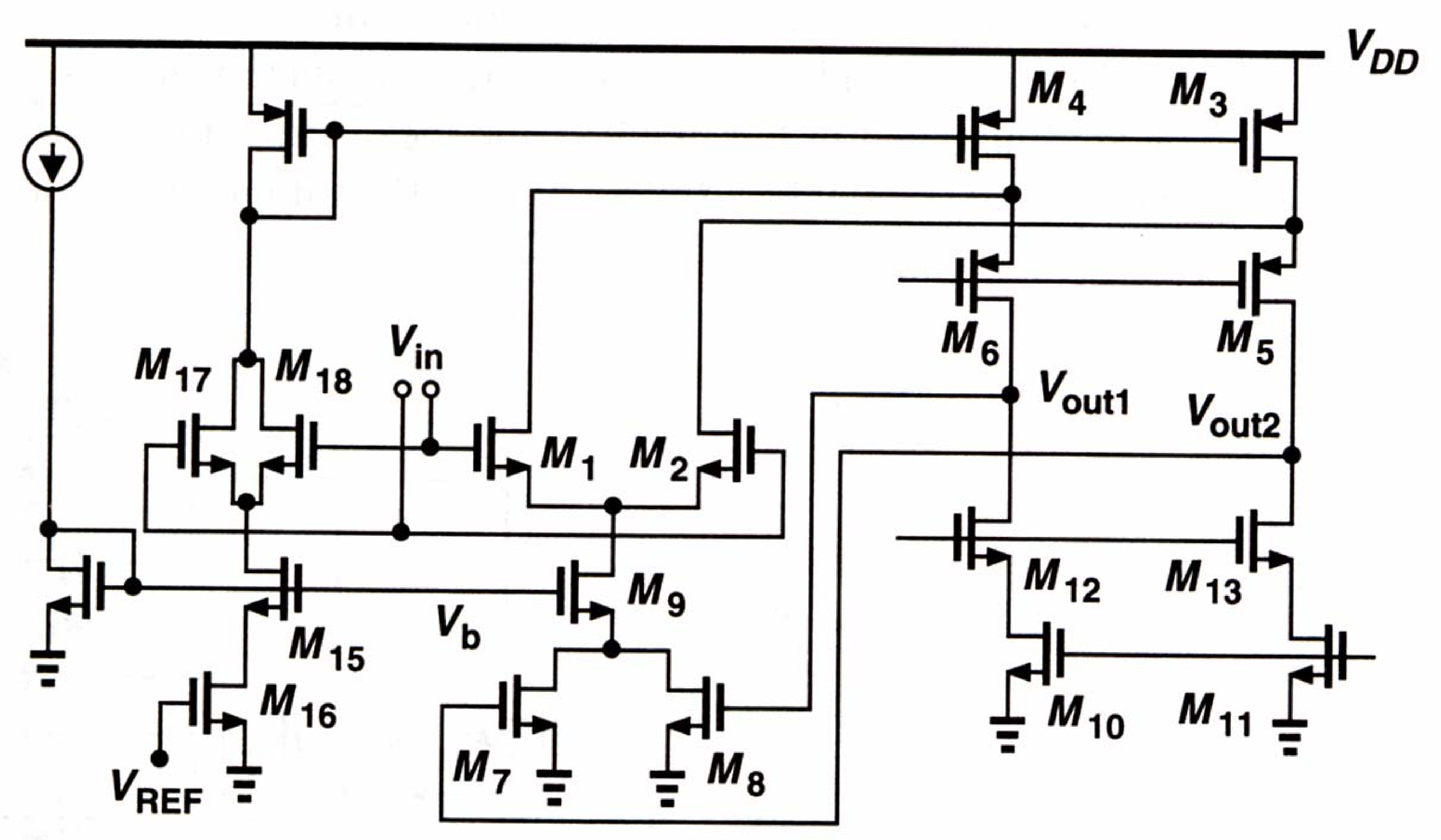
CMFB circuit using a triode TR feedback



VoutCM slightly larger than VREF because VDS(M15) >> VDS(M9)

Razavi

CMFB circuit using a triode TR feedback

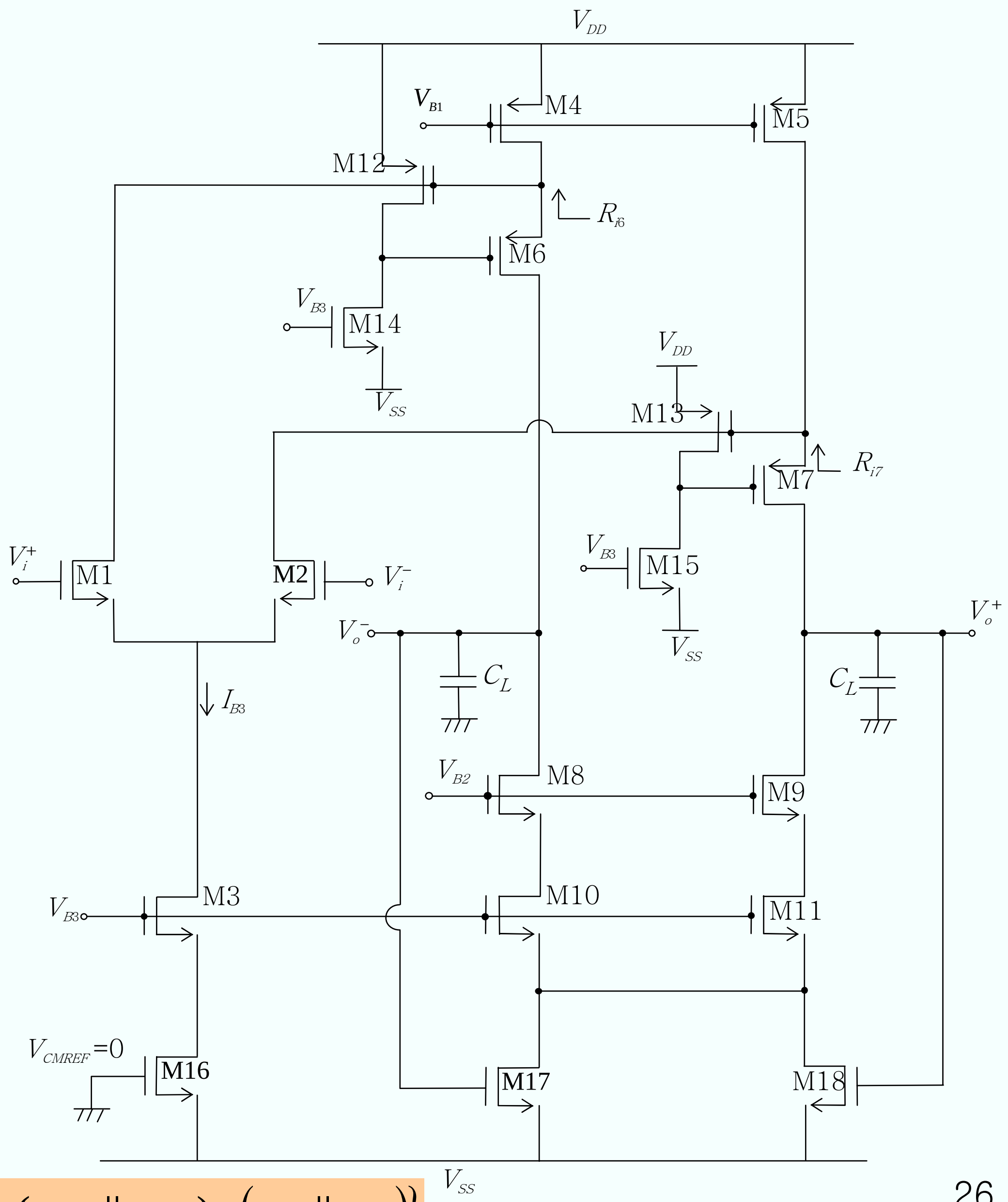


VoutCM ~= VREF

Razavi

CMFB circuit using a triode TR feedback

Fully differential Folded cascode OP amp
With gain boosting for PMOS and
Triode TR feedback CMFB



$$R_o = \{g_{m9} r_{o9} \cdot r_{o11} \cdot (\, 0.5 \cdot g_{m11} r_{o18} + 1)\} \parallel \{g_{m7} r_{o7} \cdot g_{m13}\, (r_{o13} \parallel r_{o15}) \cdot (r_{o2} \parallel r_{o5})\}$$

10.1.4 CMFB circuit 3 using a MOS differential pair (*)

VoutCM set to VcmREF
2 gain stage ➔ freq comp

$$i_{67} = \frac{1}{2} g_{m6} \cdot \left(V_o^+ - V_{CMREF}\right)$$

$$i_{98} = \frac{1}{2} g_{m6} \cdot \left(V_o^- - V_{CMREF}\right)$$

$$V_{CMFB} = 2 \cdot g_{m6} \cdot \left(\frac{r_{o6}}{2} \parallel r_{o12}\right) \cdot \left(\frac{V_o^+ + V_o^-}{2} - V_{CMREF}\right)$$

$$v_o^+ = v_o^- = -g_{m4}(r_{o4} \parallel (g_{m1} r_{o1} \cdot 2 r_{o3})) \cdot v_{CMFB} \approx -g_{m4} r_{o4} \cdot v_{CMFB}$$

$$\frac{v_o^+ + v_o^-}{2} = -g_{m4} r_{o4} \cdot v_{CMFB}$$

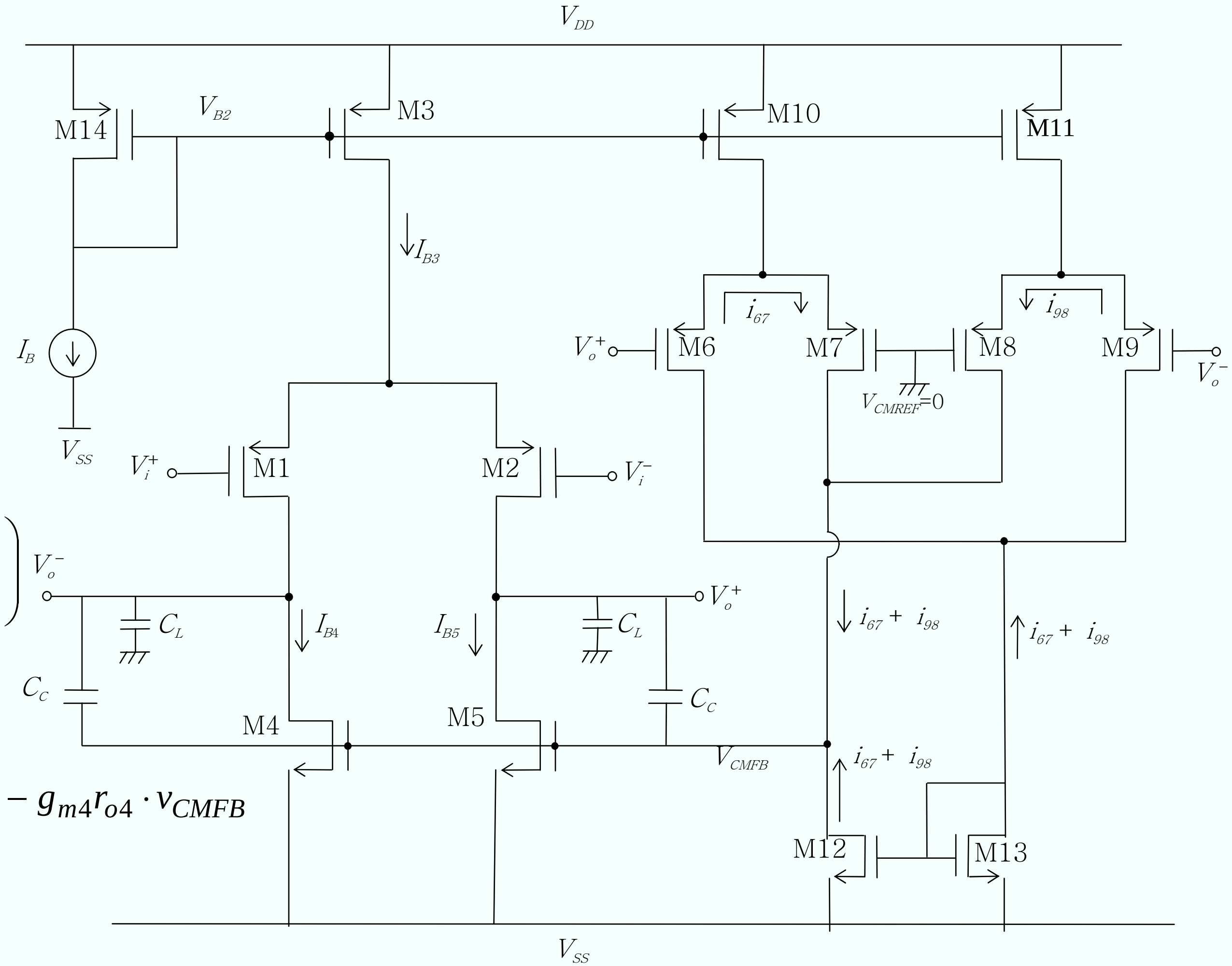


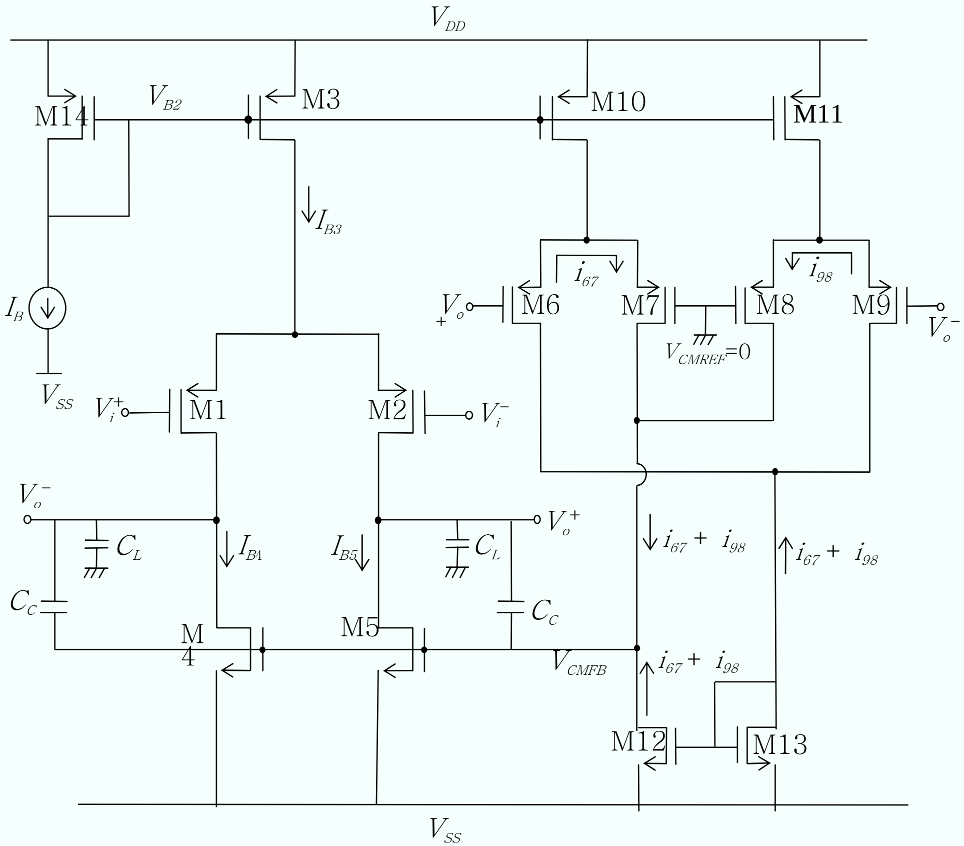
Fig 10.1.11 Fully differential OP amp using MOS differential pairs.

CMFB circuit 3 using a MOS differential pair

CMFB loop gain = $2 \cdot g_{m6} \cdot \left(0.5 r_{o6} \| r_{o12}\right) \cdot g_{m4} r_{o4}$

Error voltage = $0.5 \cdot (V_o^+ + V_o^-) - V_{CMREF}$

$$V_{OC} = \frac{(Required \quad V_{CMFB}) - \left(V_{CMFB} \,@\, 0.5(V_o^+ + V_o^-) = V_{CMREF}\right)}{Small-signal\ Voltage\ Gain\ of\ CMFB \quad circuit}$$



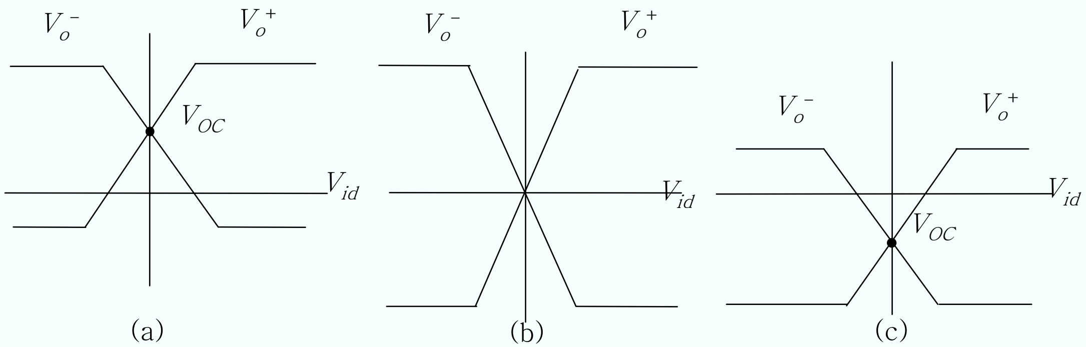


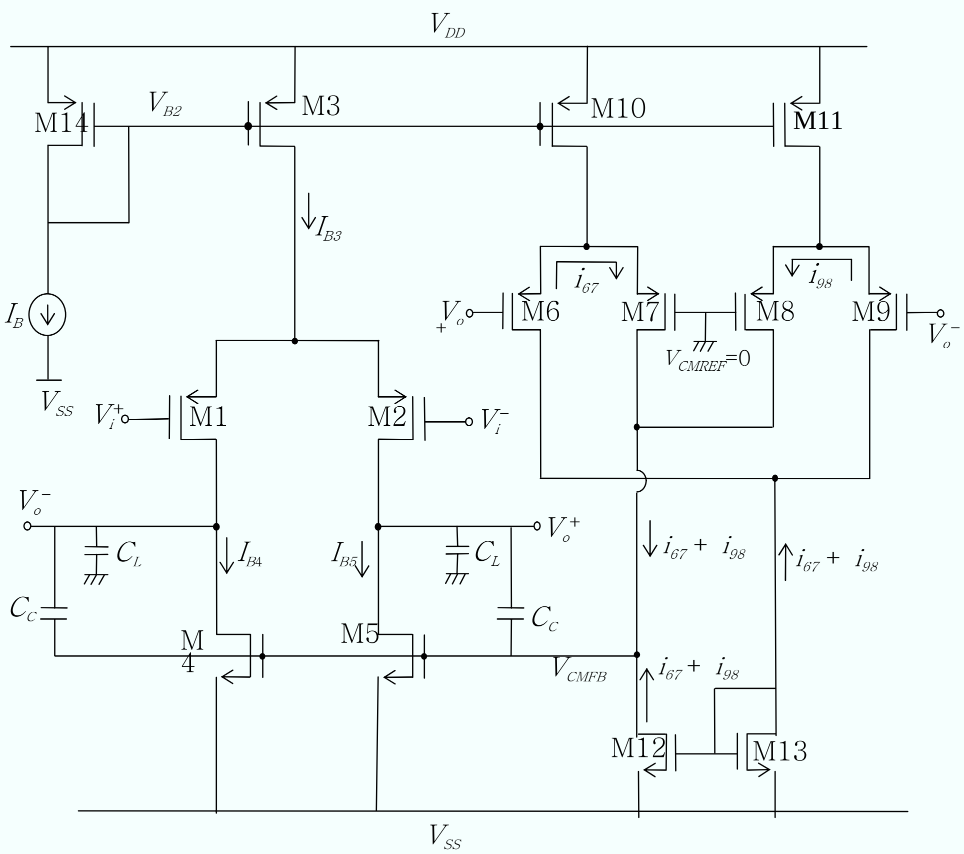
Fig 10.1.12 DC transfer curve of Fig 10.1.11 circuit for different voltage gains of CMFB circuits (a) & (c): Low CMFB gain (b) Large CMFB gain

$$\frac{(W/L)_3}{(W/L)_{10}} = 2 \cdot \frac{(W/L)_4}{(W/L)_{12}}$$

Requires a large common mode gain for small offset

CMFB circuit 3 using a MOS differential pair

Small-signal common mode voltage gain



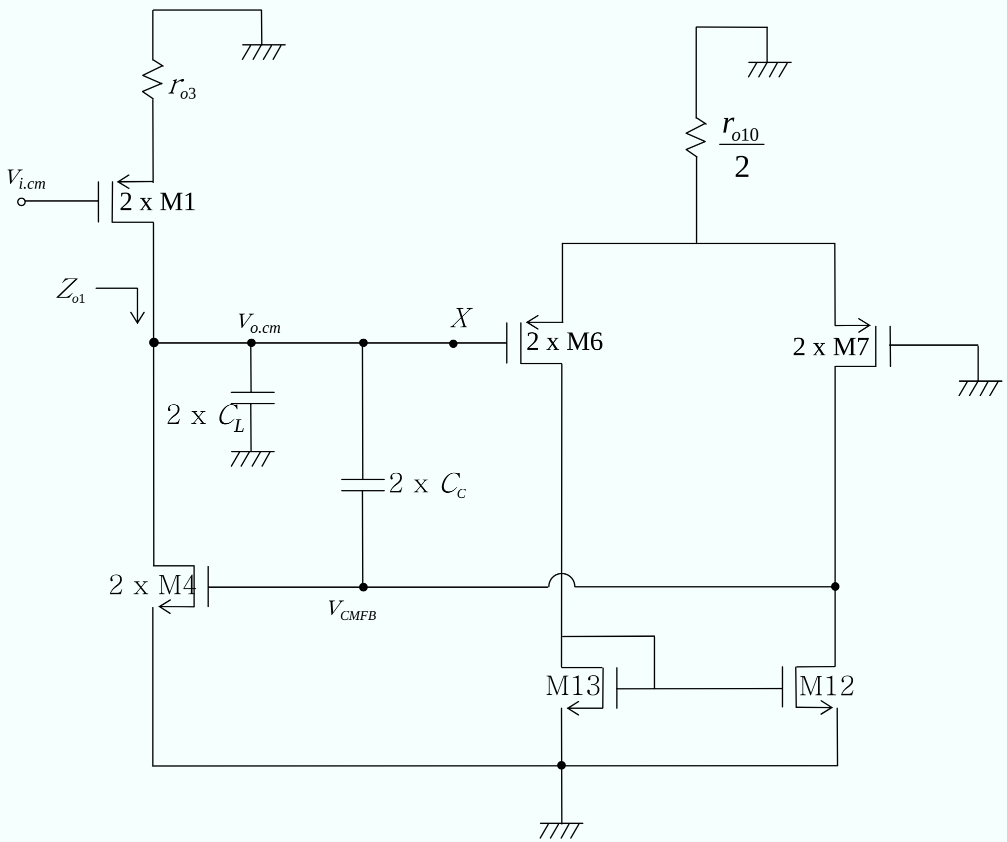


Fig 10.1.13 Common mode small-signal circuit of Fig 10.1.11 circuit

CMFB circuit 3 using a MOS differential pair

Small-signal common mode voltage gain

$$(CMFB\ \text{loop gain}) = \frac{2g_{m6}\cdot\left(\frac{r_{o6}}{2}\,\middle\|\,r_{o13}\right)\cdot g_{m4}r_{o4}}{1+s\cdot 2C_C\cdot\left(\frac{r_{o6}}{2}\,\middle\|\,r_{o13}\right)\cdot g_{m4}r_{o4}}$$

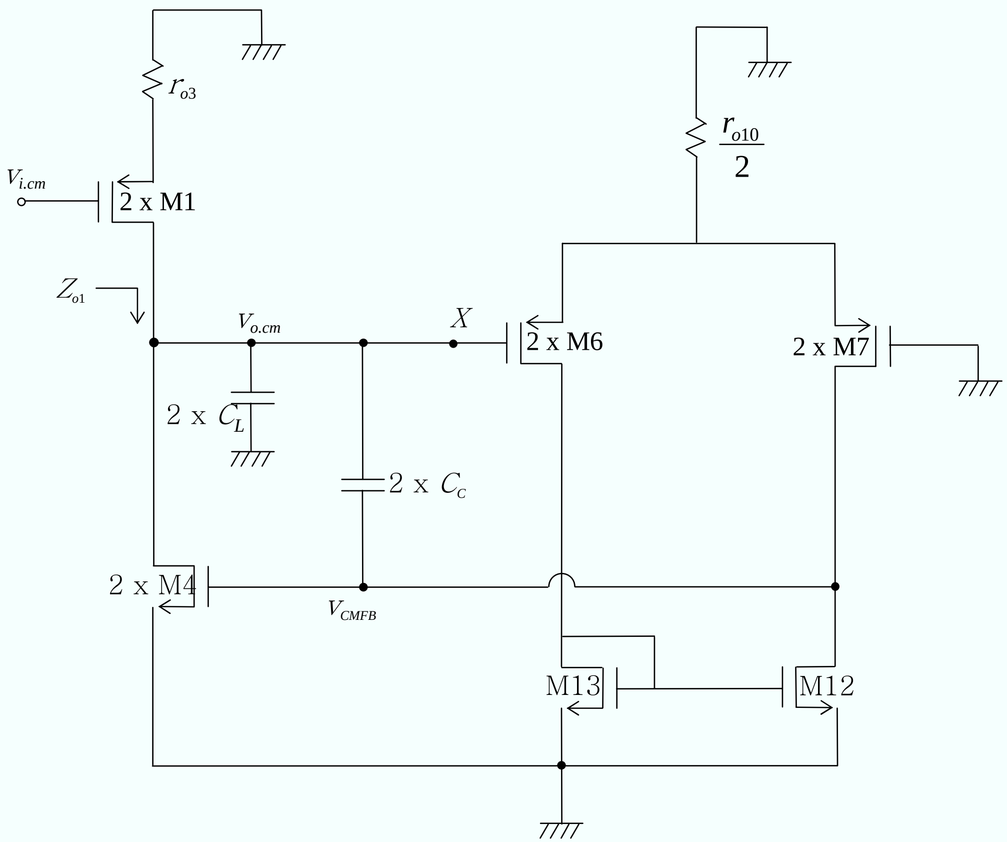
$$Z_{o1}(no\ feedback) = \frac{0.5\cdot r_{o4}}{1+s\cdot r_{o4}\cdot(C_L+C_C)}$$

$$Z_{o1}(s) = \frac{Z_{o1}(no\ feedback)}{1+(CMFB\ loop\ gain)} \approx \frac{Z_{o1}(no\ feedback)}{(CMFB\ loop\ gain)}$$

$$= \frac{1}{4\cdot g_{m6}\cdot(0.5r_{o6}\|r_{o13})\cdot g_{m4}}\cdot\frac{1+s\cdot 2C_C\cdot(0.5r_{o6}\|r_{o13})\cdot g_{m4}r_{o4}}{1+s\cdot r_{o4}\cdot(C_L+C_C)}$$

$$A_{vc}(s) \triangleq \frac{v_{o.cm}}{v_{i.cm}} = -\frac{Z_{o1}(s)\,\|\,(g_{m1}r_{o1}\cdot r_{o3})}{0.5\cdot r_{s1}+r_{o3}} \approx -\frac{Z_{o1}(s)}{r_{o3}}$$

$$= -\frac{1}{4\cdot g_{m6}\cdot((0.5r_{o6})\|r_{o13})\cdot g_{m4}r_{o3}}\cdot\frac{1+s\cdot 2C_C\cdot((0.5r_{o6})\|r_{o13})\cdot g_{m4}r_{o4}}{1+s\cdot r_{o4}\cdot(C_L+C_C)}$$



$$GBW(CMFB\ loop\ gain) = \frac{g_{m6}}{C_C}$$

CMFB circuit 3 using a MOS differential pair

Small-signal common mode voltage gain

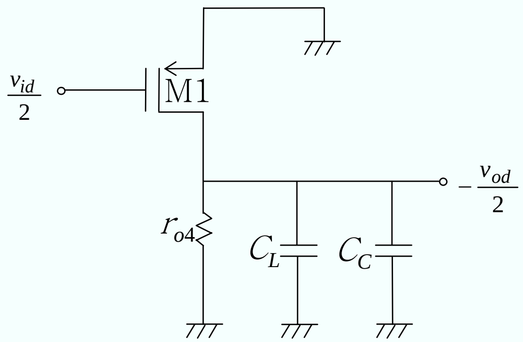
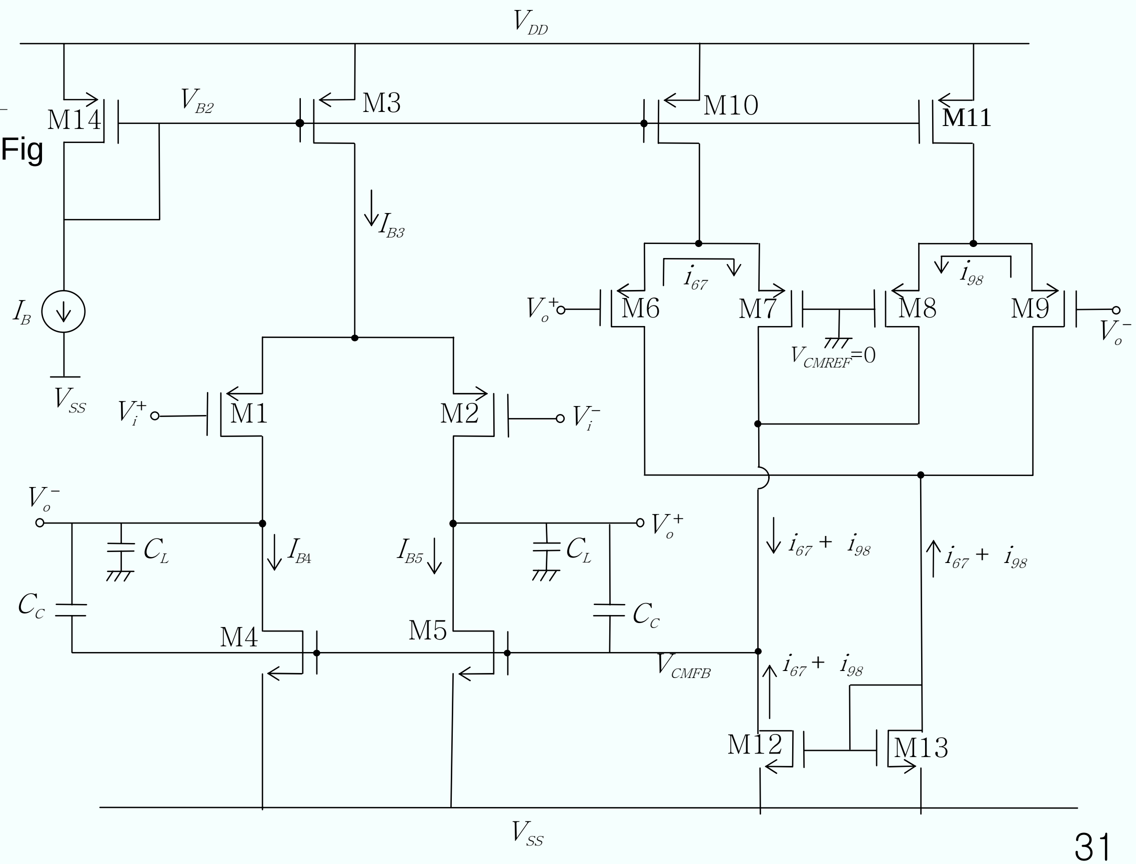


Fig 10.1.14 Small-signal differential mode half circuit of Fig 10.1.12 circuit



$$A_{vd}(s) = \frac{v_{od}}{v_{id}} = \frac{-g_{m1}\cdot(r_{o1}\|r_{o4})}{1+s\cdot(r_{o1}\|r_{o4})\cdot(C_L+C_C)}$$

$$GBW\,(A_{vd}) = \frac{g_{m1}}{C_L+C_C}$$

$$GBW(CMFB\ \ loop\ gain) = \frac{g_{m6}}{C_C}$$

CMFB circuit 3 using a MOS differential pair

Linear output voltage range of fully differential OP amp

V_o max : $\min\left[\left\{(V_i^+ \text{ or } V_i^-)+\left|V_{THp}\right|\right\},\left\{V_{DD}-\left|V_{DSAT3}\right|-\left|V_{DSAT1}\right|\right\}\right]$

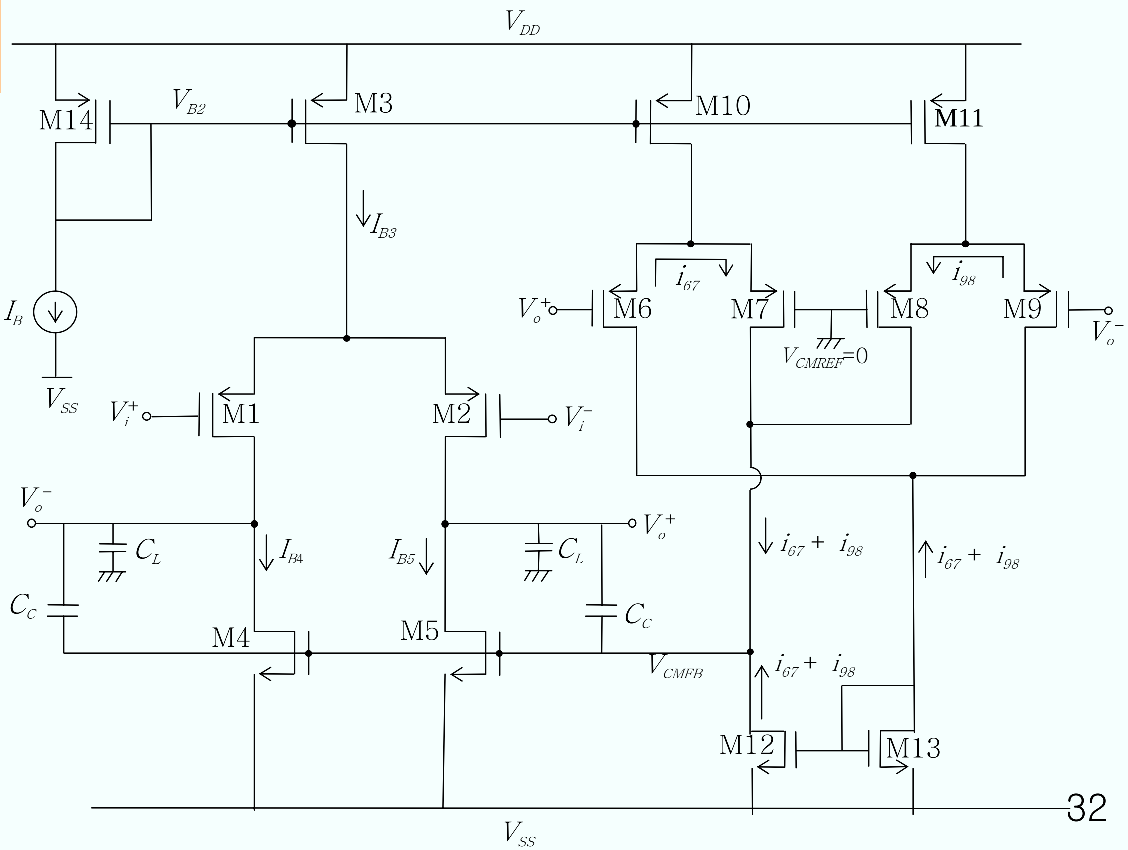
V_o min : $V_{SS}+V_{DSAT\,4}$

$V_o - V_{CMREF}$ max: $+\sqrt{2}\cdot\left|V_{DSAT6}\right|$

$V_o - V_{CMREF}$ min: $-\sqrt{2}\cdot\left|V_{DSAT6}\right|$

V_o max : $V_{CMREF}+\sqrt{2}\cdot\left|V_{DSAT6}\right|$

V_o min : $V_{CMEF}-\sqrt{2}\cdot\left|V_{DSAT6}\right|$



CMFB circuit 3 using a MOS differential pair

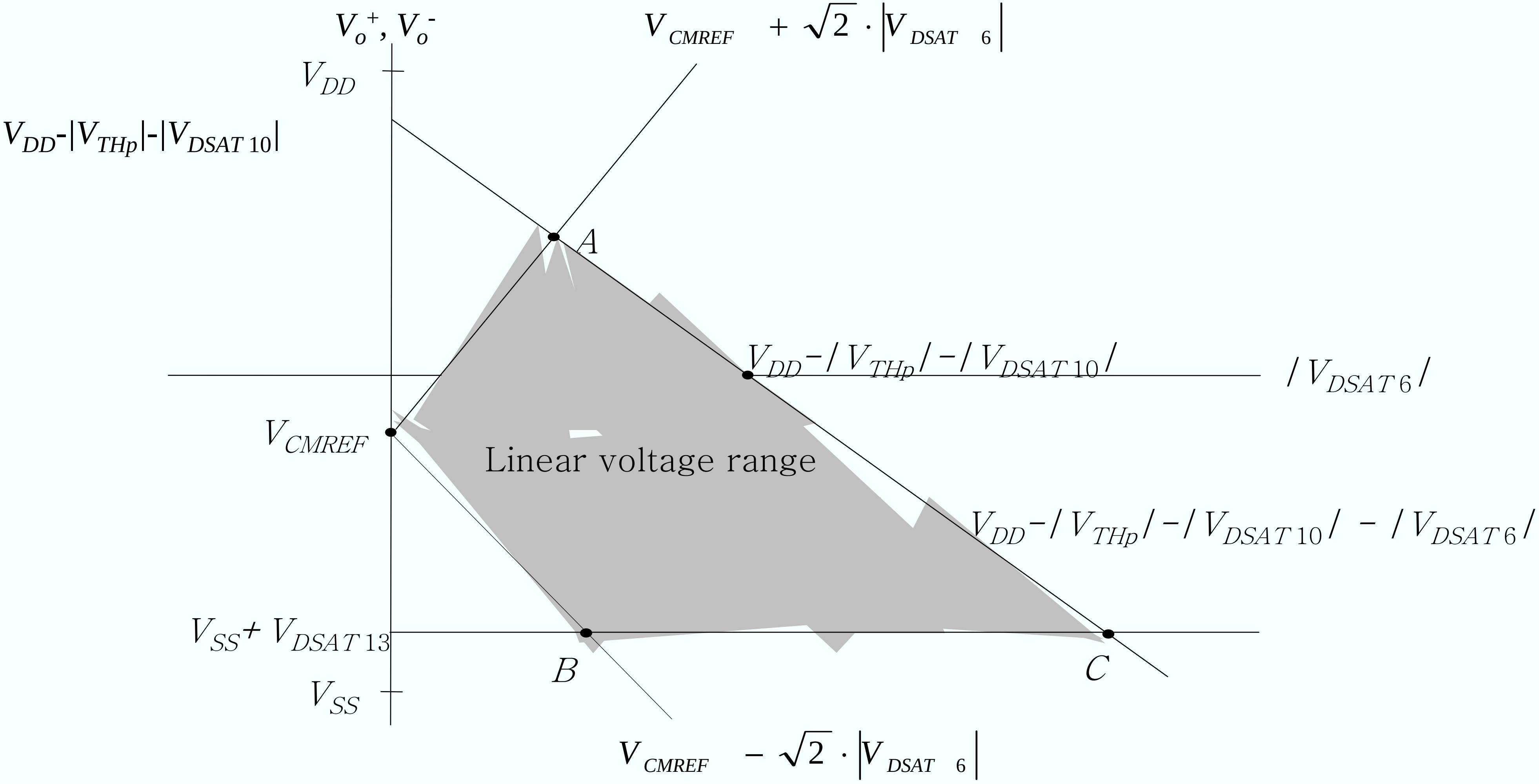


Fig 10.1.15 Linear voltage range

CMFB circuit 3 using a MOS differential pair

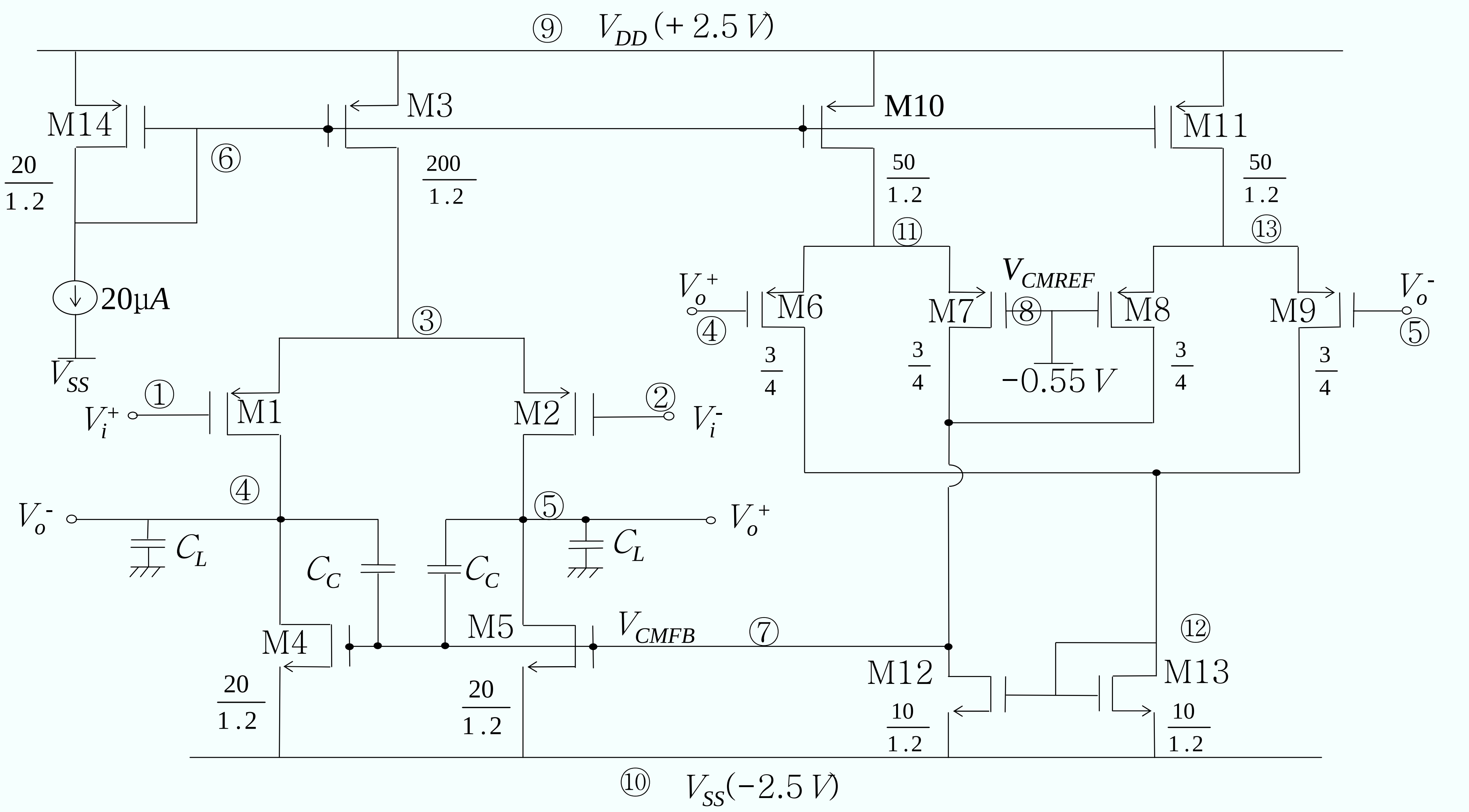


Fig 10.1.17 Example design of Fig. 10.1.11 circuit

CMFB circuit 3 using a MOS differential pair


```
Fully differential CMOS amplifier with diff.pair CMFB ckt.
main diff amp
*
m1  4  1  3  9  pmos  w=300u  l=1.2u  ad=1080p  as=1080p  pd=307u  ps=307u
m2  5  2  3  9  pmos  w=300u  l=1.2u  ad=1080p  as=1080p  pd=307u  ps=307u
m3  3  6  9  9  pmos  w=200u  l=1.2u  as=720p  as=720p  pd=207u  ps=207u
m4  4  7  10  10  nmos  w=20u  l=1.2u  ad=72p  as=72p  pd=27u  ps=27u
m5  5  7  10  10  nmos  w=20u  l=1.2u  ad=72p  as=72p  pd=27u  ps=27u
*
CMFB ckt.
*
m6  12  4  11  9  pmos  w=3u  l=4. 0u  ad=11p  pd=10u  as=11p  ps=10u
m7   7  8  11  9  pmos  w=3u  l=4. 0u  ad=11p  pd=10u  as=11p  ps=10u
m8   7  8  13  9  pmos  w=3u  l=4. 0u  ad=11p  pd=10u  as=11p  ps=10u
m9  12  5  13  9  pmos  w=3u  l=4. 0u  ad=11p  pd=10u  as=11p  ps=10u
*
current sources for CMFB
*
m10  11  6  9  9  pmos  w=50u  l=1.2u  ad=180p  pd=57u  as=180p  pd=57u
m11  13  6  9  9  pmos  w=50u  l=1.2u  ad=180p  pd=57u  as=180p  pd=57u
high gain for CMFB ckt.
*
m12   7  12  10  10  nmos  w=10u  l=1.2u  ad=36p  pd=17u  as=36p  ps=17u
*
low gain for CMFB ckt.
*
*m12   7  7  10  10  nmos  w=10u  l=1.2u  ad=36p  pd=17u  as=36p  ps=17u
m13  12  12  10  10  nmos  w=10u  l=1.2u  ad=36p  pd=17u  as=36p  ps=17u
*
bias ckt
```

CMFB circuit 3 using a MOS differential pair


```
*
m14  6  6  9  9  pmos  w=20u  l=1.2u  ad=72p  as=72p  pd=27u  ps=27u
idd  6  10  dc  20u
*
*  bias voltages
*
vcmref  8  0  dc  -0.55
vi1  1  0  dc  0  ac  0.5
vi2  2  0  dc  0  ac  -0.5
*
*  supply voltages
*
vdd   9  0  dc  2.5
vss  10  0  dc  -2.5
*
*  load capacitors
*
cl1  4  0  10p
cl2  5  0  10p
*
** compensation capacitor
*
cc1  7  4  1p
cc2  7  5  1p
.op
```

CMFB circuit 3 using a MOS differential pair


```
*.dc vi1 -2.5 2.5 .01
.dc vi1 -50m 50m 0.1m
.probe v(5) v(40) v(11) v(7) v(12) v(6) v(3) v(13)
.print dc v(4)
.print dc v(5)
.ac dec 10 1 gig
.print ac vdb(5)
.print ac vp(5)
*.tran 0.01 10
*.print tran v(4)
*.print tran v(5)
.model nmos nmos tox=200e-10 uo=500 vto=0.8 gamma=0.0
+ lambda=0.08 cgdo=300p cgso=300p cj=2.75e-4 cjsw=1.9e-10
+ ld=0.2u level=1 af=1 kf=5e-26
.model pmos pmos tox=200e-10 uo=200 vot=-0.8 gamma=0.0
+ lambda=0.1 cgdo=300p cgso=300p cj=2.75e-4 cjsw=1.9e-10
+ ld=0.2u level=1 af=1 kf=1e-26
.end
```

Fig 10.1.18 SPICE netlist of Fig.10.1.17 circuit

CMFB circuit 3 using a MOS differential pair

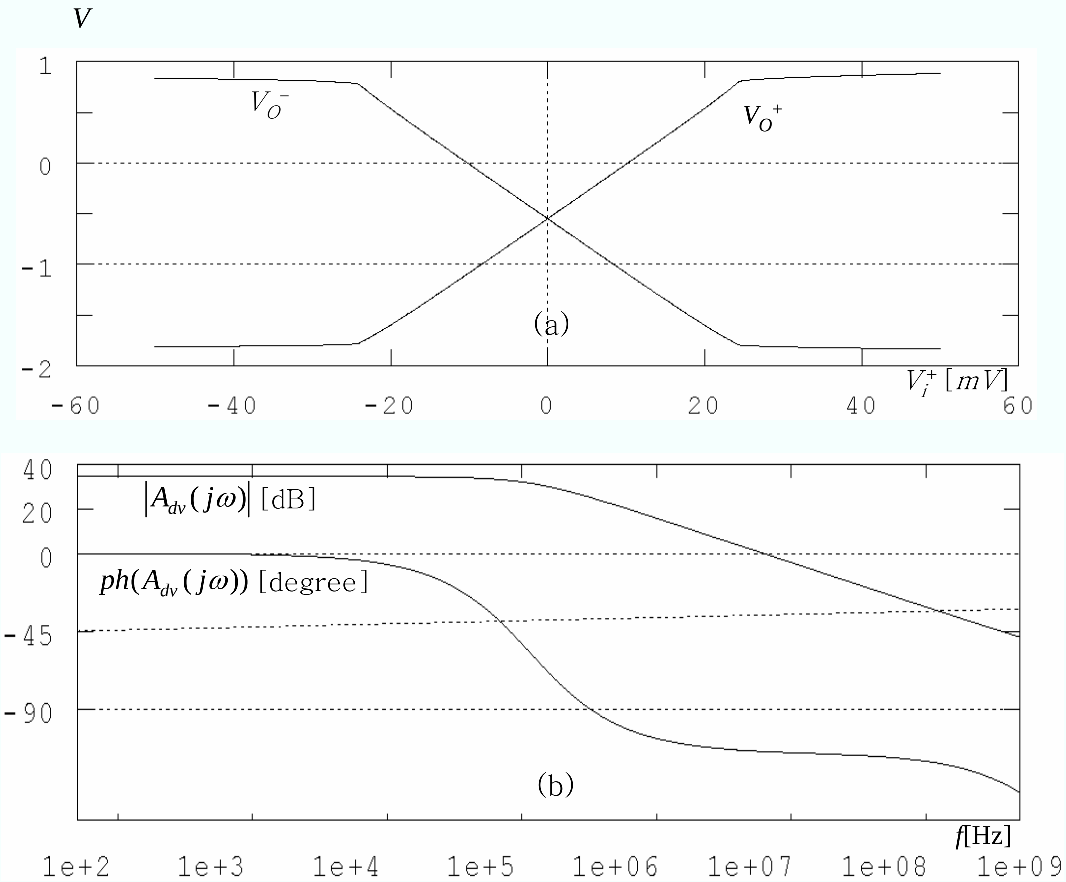


Fig 10.1.19 SPICE simulation results of Fig. 10.1.17 circuit
(a) DC transfer curve (b) Differential mode voltage gain (c) Common mode voltage gain

CMFB circuit 3 using a MOS differential pair

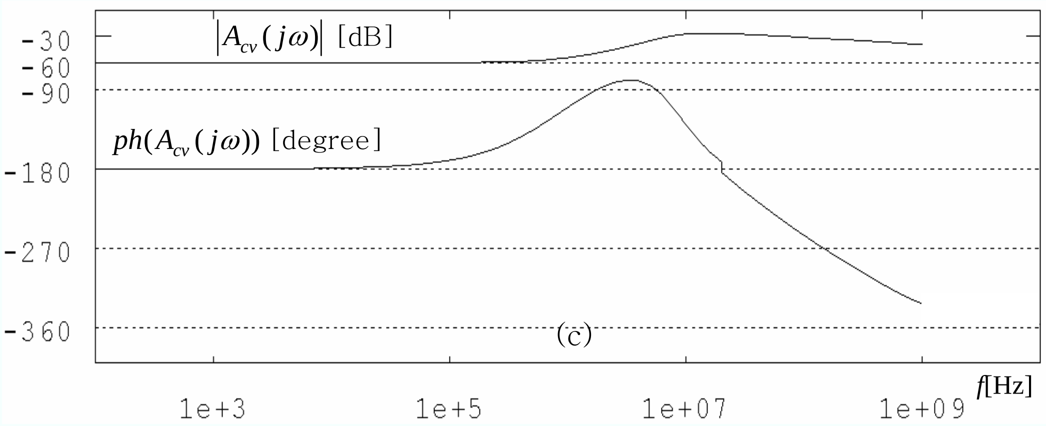


Fig 10.1.19 SPICE simulation results of Fig. 10.1.17 circuit
(a) DC transfer curve (b) Differential mode voltage gain (c) Common mode voltage gain