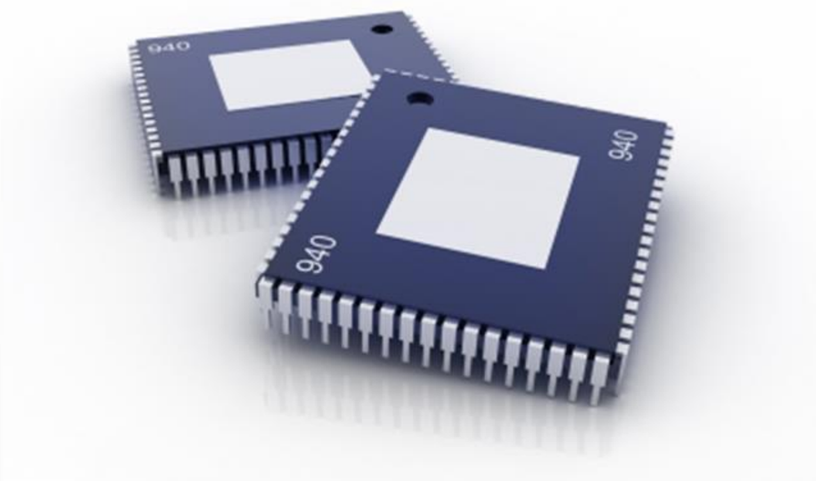

LECTURE 2

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3. Basic Current Mirrors and Single-Stage Amplifiers

3.1 Simple CMOS Current Mirrors

3.2 Common-Source Amplifier

3.3 Source-Follower or Common-Drain Amplifier

3.4 Common-Gate Amplifier

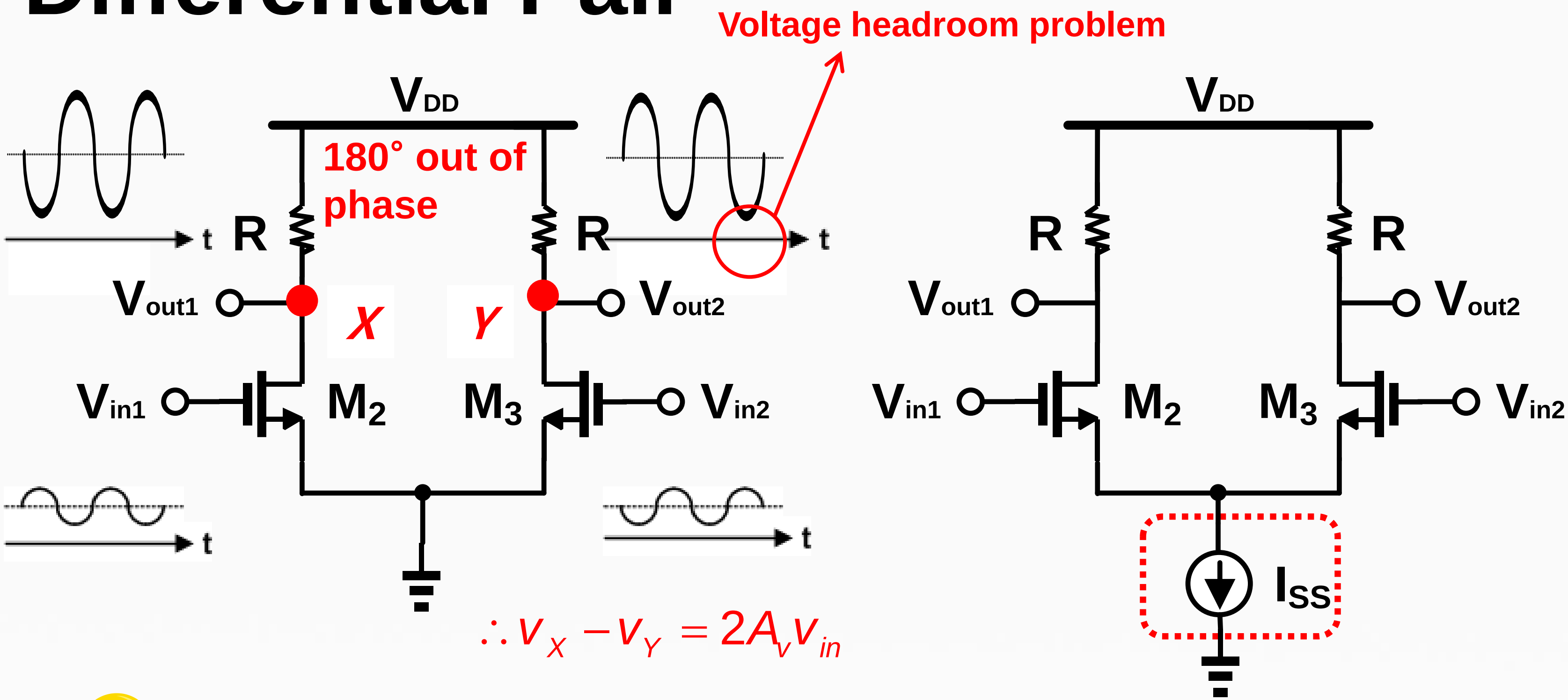
3.5 Source-Degenerated Current Mirrors

3.6 Cascode Current Mirrors

3.7 Cascode Gain Stage

3.8 MOS Differential Pair and Gain Stage

Differential Pair



$$\therefore v_X - v_Y = 2A_v v_{in}$$

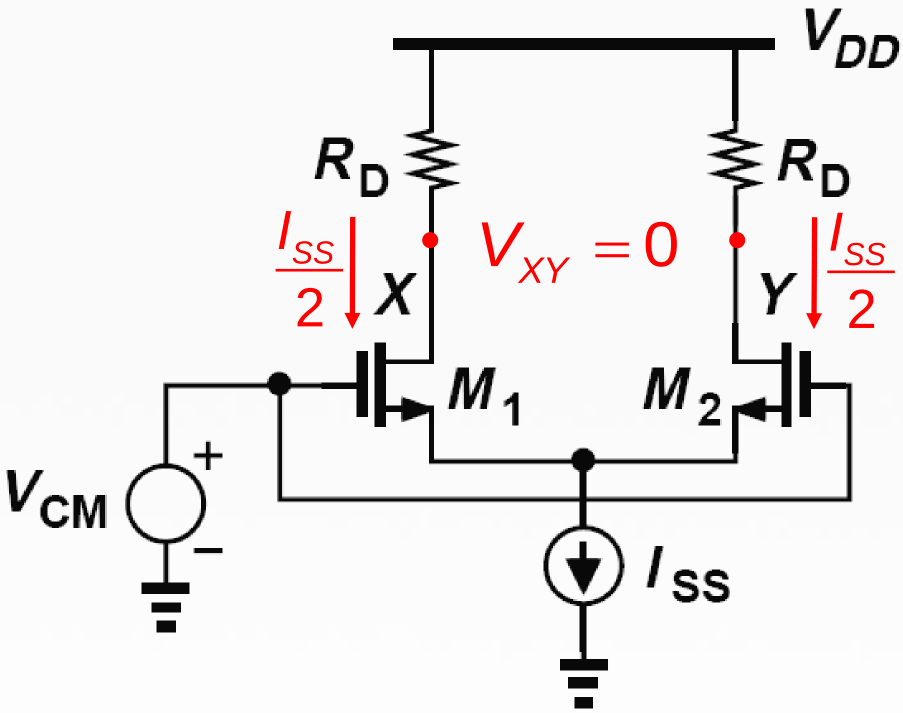
Constant current source
(Tail current source)

Merits

1. High noise rejection
2. High output swings

The g_m and the output CM level are varying

Common-Mode Response



$$V_{G1} = V_{G2} = V_{CM}, \quad I_{D1} = I_{D2} = \frac{I_{SS}}{2}$$

$$V_X = V_Y = V_{DD} - R_D \frac{I_{SS}}{2}$$

$$V_{out,CM} \Rightarrow V_{XY} = 0$$

For operation in saturation region

$$V_{DS} > V_{GS} - V_{TH}$$

$$V_D > V_G - V_{TH}$$

$$V_{CM} < V_{DD} - R_D \frac{I_{SS}}{2} + V_{TH}$$

Example 1

a) Gain이 5이고 Power consumption이 2mW인 NMOS differential pair를 설계하는데, differential pair를 따르는 단이 적어도 1.6V의 Output CM level을 요구하는 것을 조건으로 한다. $\boldsymbol{\mu_n C_{ox} = 100\mu A/V^2, \lambda = 0}$**, 그리고** $\boldsymbol{V_{DD} = 1.8V}$**로 가정한다. 이때 W/L을 구하여라.**

Sol) 한계 전력 소모와 $\boldsymbol{V_{DD}}$로부터 I_{ss}를 구한다.

$$I_{SS} = 1.11mA$$

Output CM level은 다음과 같다.

$$V_{CM,out} = V_{DD} - R_D \frac{I_{SS}}{2}$$

$\boldsymbol{V_{CM,out} = 1.6V}$**를 위해서 계산을 하면** $\boldsymbol{R_D}$**는 다음과 같다.**

$$R_D \le \frac{2}{I_{SS}}\left(V_{DD} - 1.6\right) \rightarrow R_D = 360\Omega$$

$\boldsymbol{g_m R_D = 5}$**이고, 각 트랜지스터에** $\boldsymbol{\frac{I_{ss}}{2}}$**가 흐르므로**

$$g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} \frac{I_{ss}}{2}} = \frac{5}{360\Omega}$$

이에 따라서 W/L은 $\frac{W}{L} = 1738$ 가 된다.

Example 1

b) (a)의 예제에서 $\boldsymbol{V_{TH}=0.4V}$라면 허용 가능한 최대 input CM level은 얼마인가?

Sol) $\boldsymbol{V_{CM,in}}$은 다음과 같이 정리 할 수 있다.

$$V_{CM,in} < V_{DD} - R_D\frac{I_{SS}}{2} + V_{TH}$$

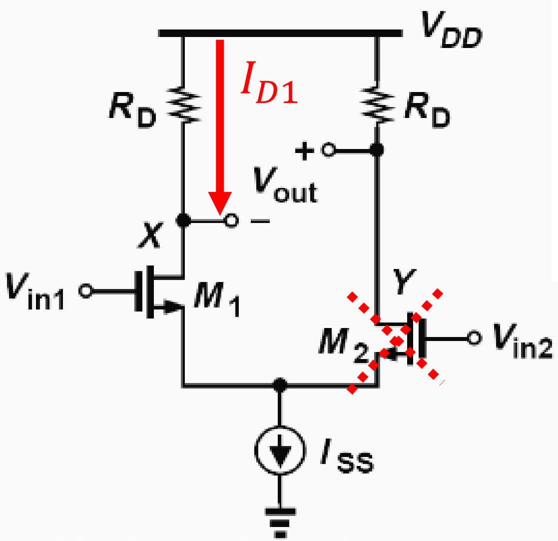
$\boldsymbol{V_{CM,out} = V_{DD} - R_D\frac{I_{SS}}{2}}$ 이므로 정리하면 다음과 같다.

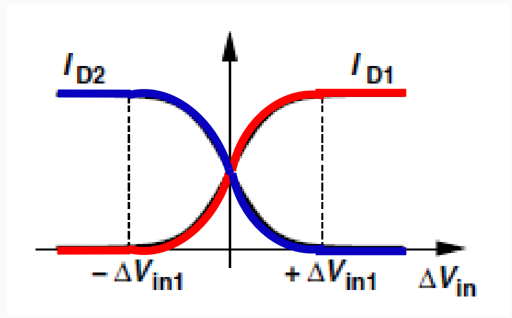
$$V_{CM,in} < V_{CM,out} + V_{TH}$$

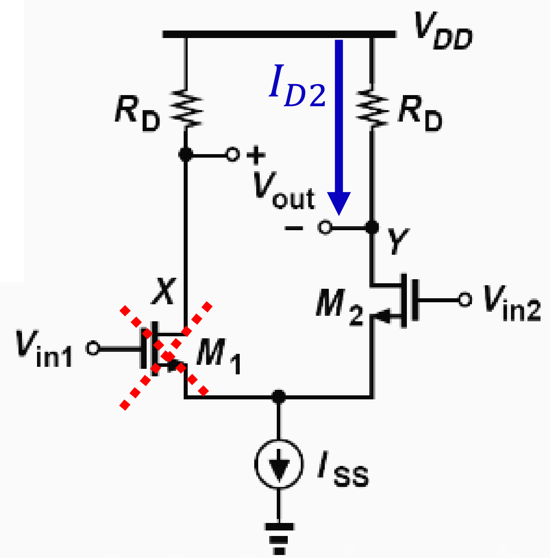
$\boldsymbol{V_{CM,out} = 1.6V,\ V_{TH} = 0.4V}$ 이므로

$$V_{CM,in} < 2V$$

Differential Response







$V_{in1} > V_{in2}$

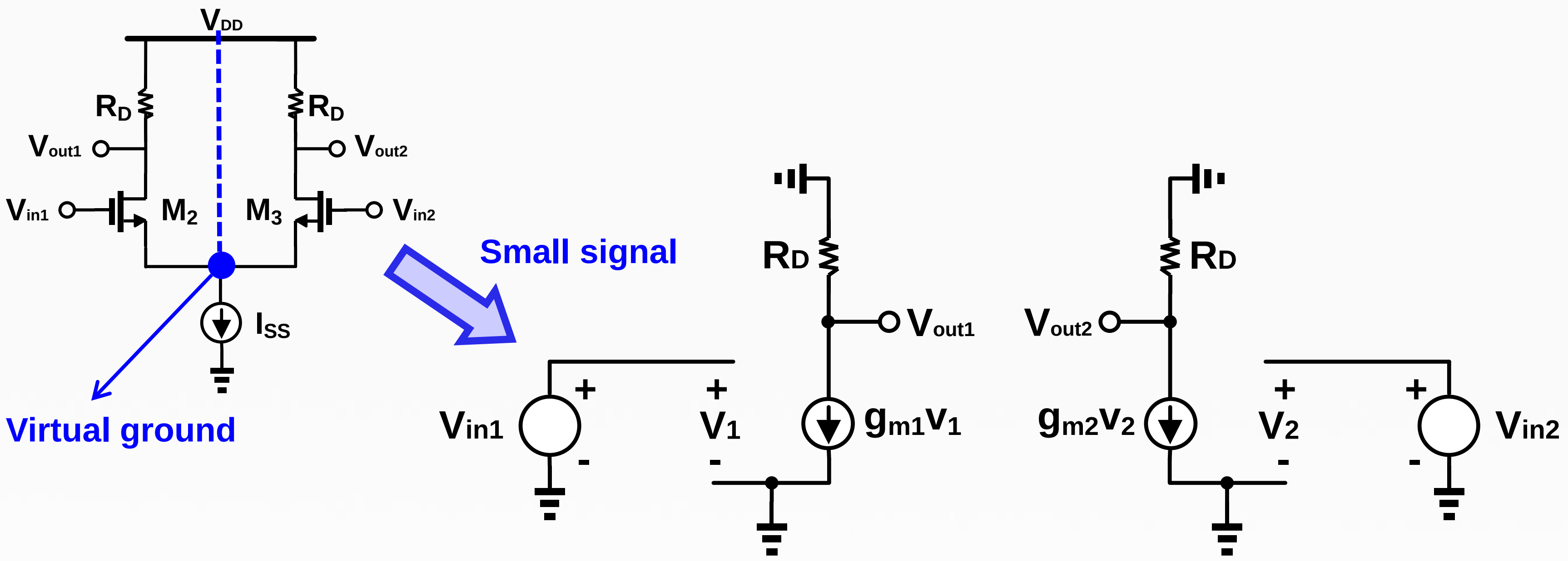
$$I_{D1} = I_{SS}$$
$$I_{D2} = 0$$
$$V_X = V_{DD} - R_D I_{SS}$$
$$V_Y = V_{DD}$$

$V_{in1} < V_{in2}$

$$I_{D2} = I_{SS}$$
$$I_{D1} = 0$$
$$V_Y = V_{DD} - R_D I_{SS}$$
$$V_X = V_{DD}$$

Small-Signal Response

❖ Virtual Ground and Half Circuit

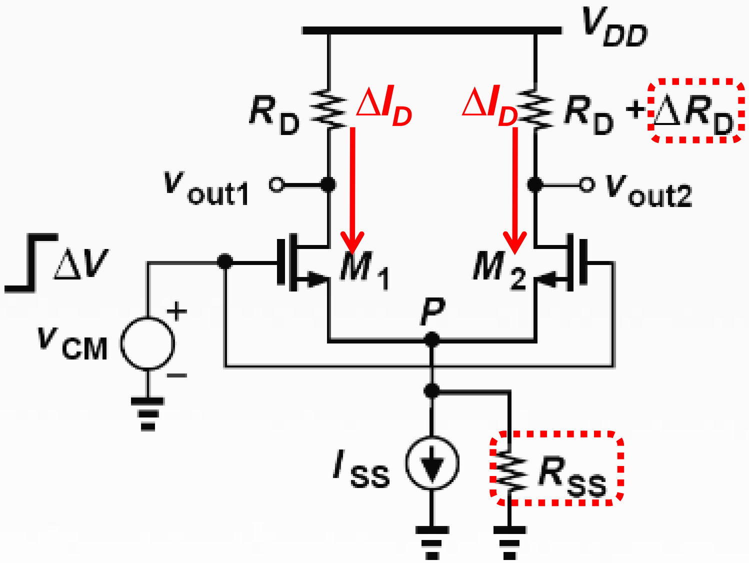


$$V_{out1} = -g_{m1} R_D V_{in1}$$
$$V_{out2} = -g_{m2} R_D V_{in2}$$

$$\Rightarrow \quad A_V = \frac{V_{out1} - V_{out2}}{V_{in1} - V_{in2}} = -g_{m1,2} R_D$$

CM to DM Conversion, $A_{CM\text{-}DM}$

Asymmetric loads(ΔR_D)



$$\Delta V_{CM} = \Delta V_{GS} + 2\Delta I_D R_{SS}$$

since $\Delta V_{GS} = \Delta I_D / g_m$,

$$\Delta V_{CM} = \Delta I_D (1/g_m + 2R_{SS})$$

$$\Delta I_D = \frac{\Delta V_{CM}}{1/g_m + 2R_{SS}}$$

$$\Delta V_{out} = \Delta V_{out1} - \Delta V_{out2}$$
$$= \Delta I_D R_D - \Delta I_D (R_D + \Delta R_D)$$
$$= -\Delta I_D \Delta R_D$$
$$= -\frac{\Delta V_{CM}}{1/g_m + 2R_{SS}} \Delta R_D$$

$$\therefore \left|A_{CM-DM}\right| = \left|\frac{\Delta V_{out}}{\Delta V_{CM}}\right| = \frac{\Delta R_D}{\frac{1}{g_m} + 2R_{SS}}$$

In ideal case,

$R_{SS} \rightarrow \infty$,

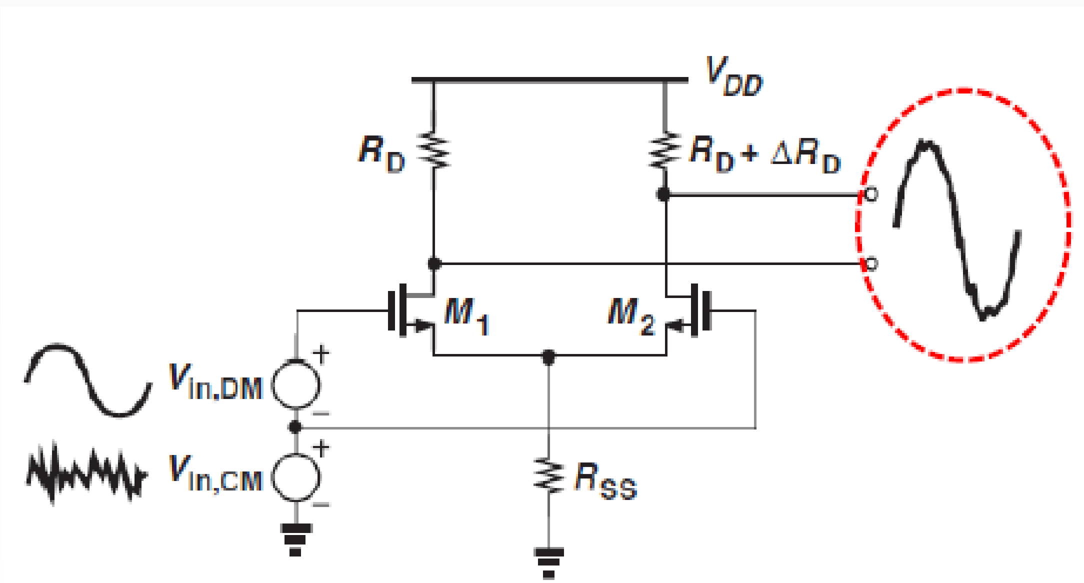
$\Delta R_D \rightarrow 0$,

$\therefore A_{CM-DM} = 0$

CMRR

Common-mode rejection ratio (CMRR)

: **Input**의 **Common noise**의 **Variation**이 얼만큼 **output**에서 제거되는가



$$CMRR = \left| \frac{A_{DM}}{A_{CM-DM}} \right| = \frac{g_m \cdot R_D}{\dfrac{\Delta R_D}{\dfrac{1}{g_m} + 2R_{SS}}}$$

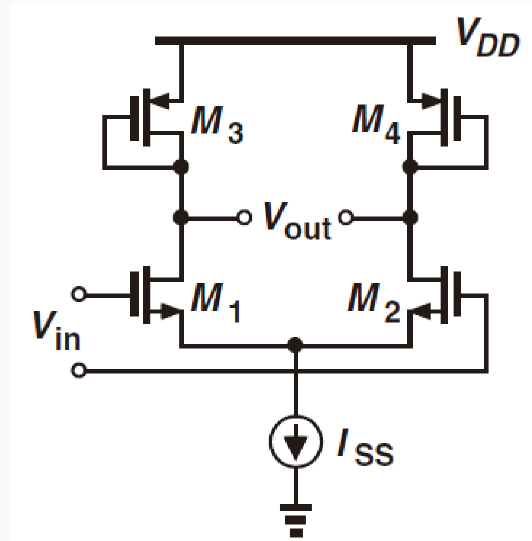
In ideal case

$A_{CM-DM} = 0,$

$\therefore CMRR \rightarrow \infty$

Example 2

$W_3 = 10\mu m, W_4 = 11\mu m$ 일 때 CMRR를 구하여라.



Sol) CMRR은 다음과 같이 정리 할 수 있다.

$$CMRR = \frac{g_m \cdot R_D}{\dfrac{\Delta R_D}{\dfrac{1}{g_m} + 2R_{ss}}} = \frac{1 + 2g_{m1}R_{SS}}{\dfrac{\Delta R_D}{R_D}}$$

$M_{3,4}$는 R로 바꾸어주면 다음과 같다.

$$R_{D1} = \frac{1}{g_{m3}}, R_{D2} = \frac{1}{g_{m4}}$$

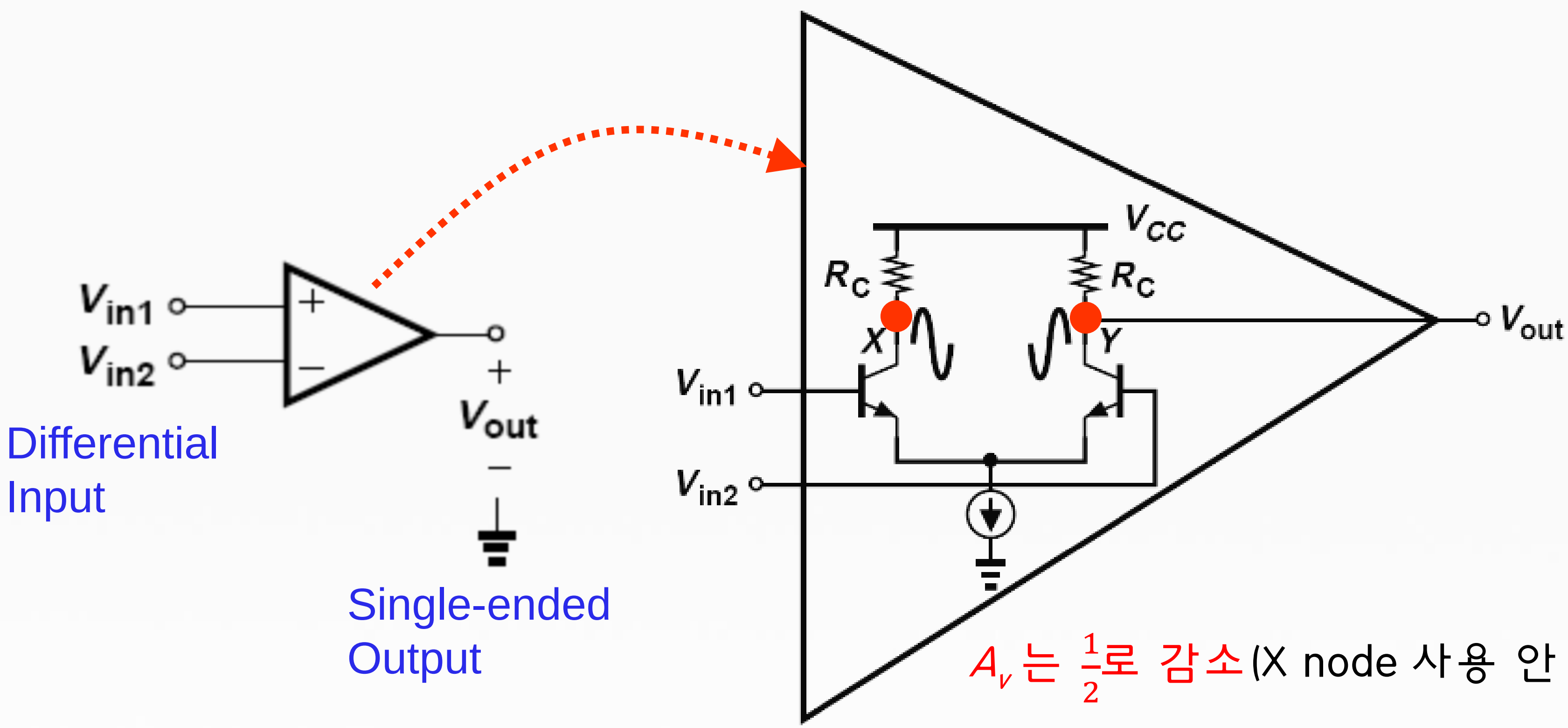
R 값이 위와 같을 때 Miss match를 계산해주면,

$$\frac{\Delta R_D}{R_D} = \frac{R_{D1} - R_{D2}}{R_{D1}} = 1 - \frac{R_{D2}}{R_{D1}} = 1 - \frac{g_{m3}}{g_{m4}} = 1 - \frac{\sqrt{2\mu_p C_{ox}(\frac{W}{L})_3 I_D}}{\sqrt{2\mu_p C_{ox}(\frac{W}{L})_4 I_D}} = 1 - \sqrt{\frac{10}{11}} = 0.0465$$

위의 CMRR의 수식에 대입을 하면,

$$CMRR = 2248$$

Differential to Single-ended Conversion

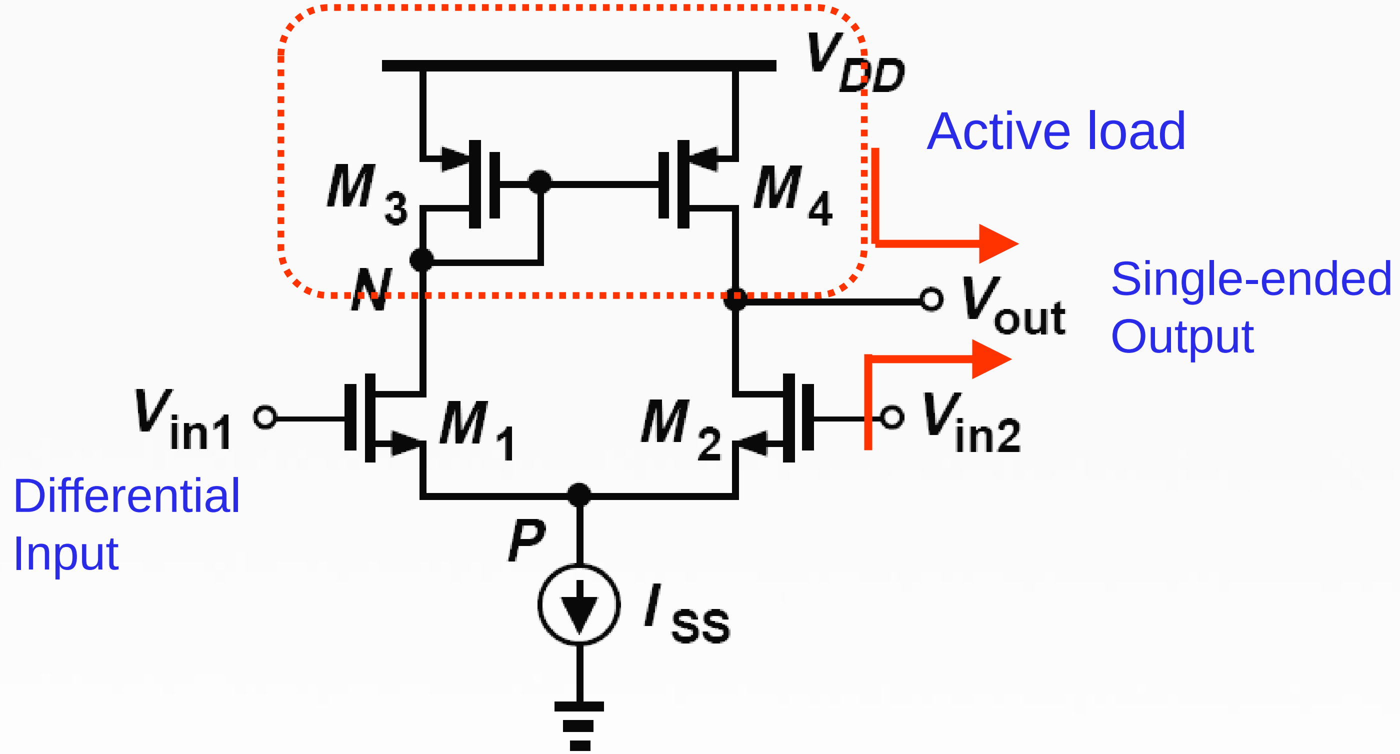


A_v 는 $\frac{1}{2}$로 감소(X node 사용 안 함)

Many circuits require a differential to single-ended conversion, however, the above topology is not very good.(A_v 감소)

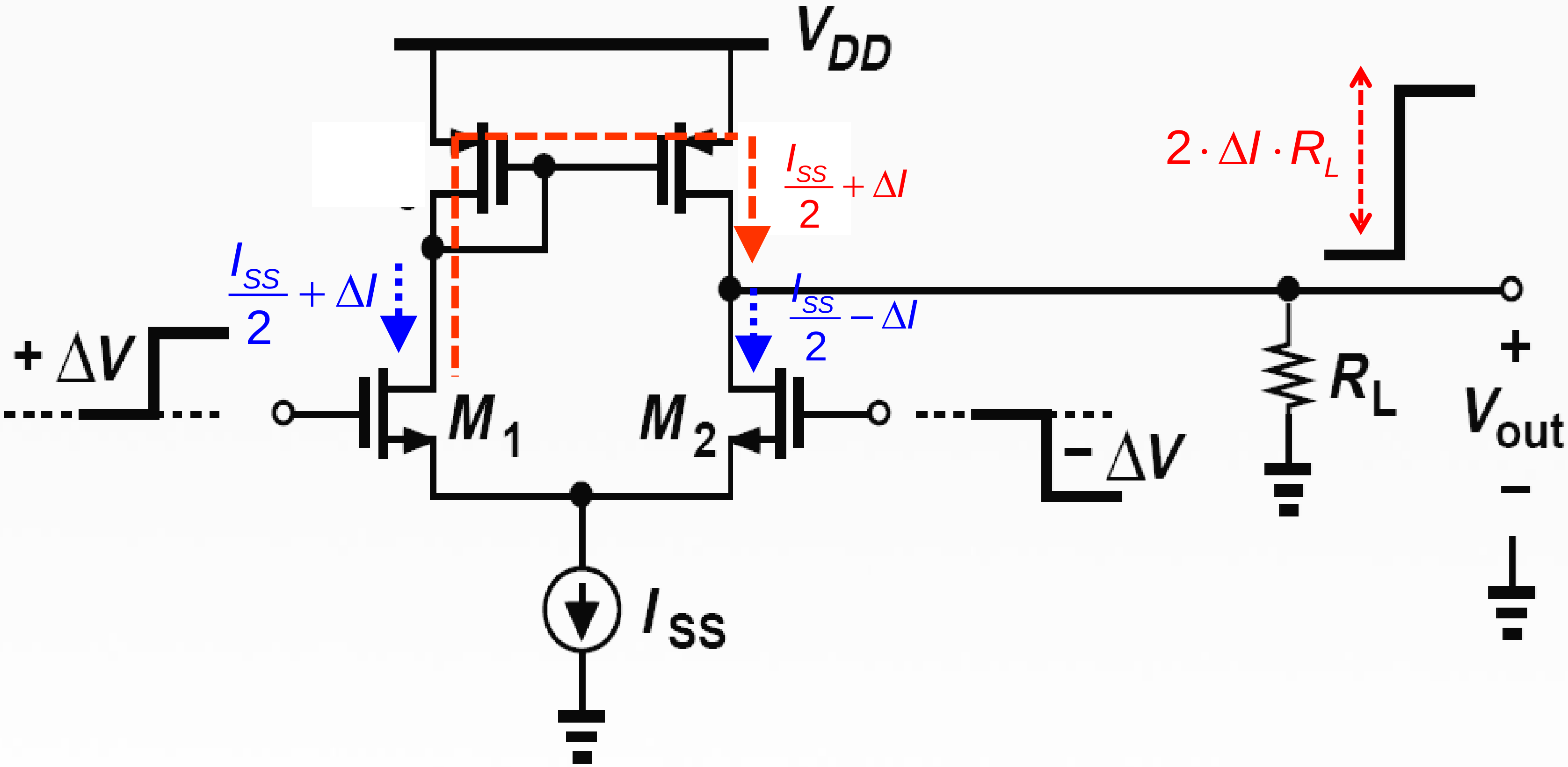
Better Alternative

❖ **Active load – Current mirror**



This circuit topology performs differential to single-ended conversion with no loss of gain.

MOS Differential Pair with Active Load



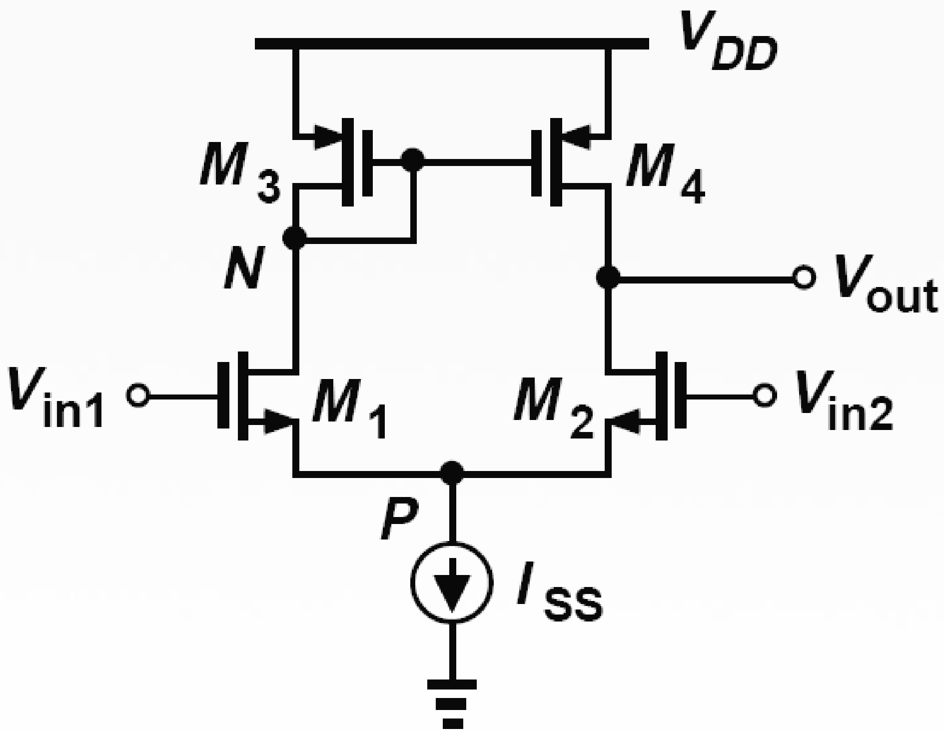
This type of load is different from the conventional “static load” and is known as an “active load”.

How are the gain calculated?

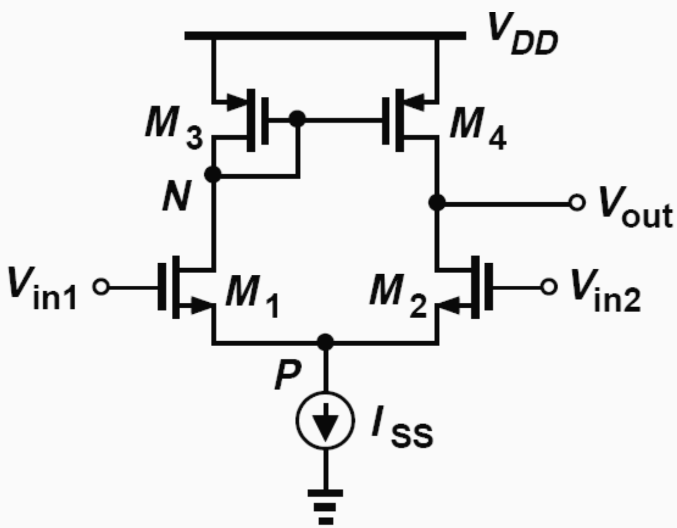
❖ Gain? -> half circuit (Asymmetric load)

-> ① Small signal

② Thevenin equivalent



Use the small signal



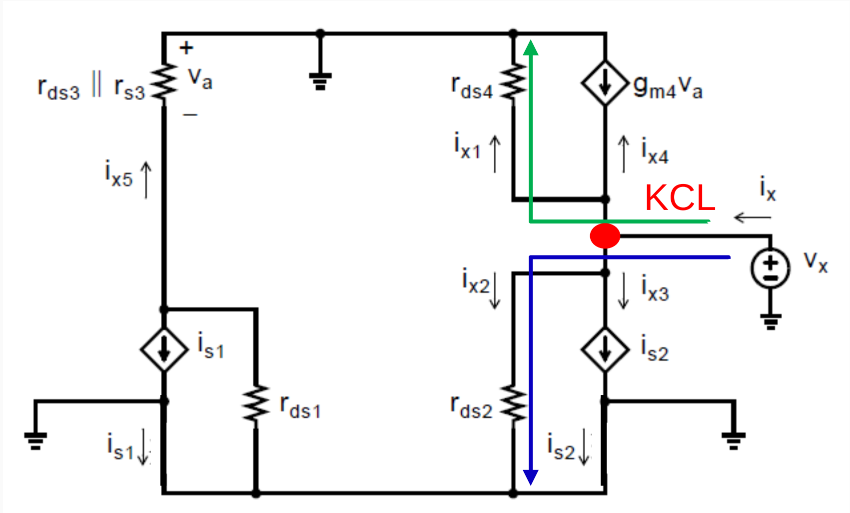


Fig. 3.20 The small-signal model

Use the KCL

$$i_X = i_{X1} + i_{X2} + i_{X3} + i_{X4}$$

$$i_{X1} = \frac{V_X}{r_{ds4}} \quad i_{X2} = \frac{V_X}{r_{ds2}} \quad (3.73, 3.74)$$

Since $i_{X2} = i_{S1} + i_{S2}$

$$i_{s1} = i_{s2} = -\frac{V_x}{2r_{ds2}} \quad (3.75)$$

Current mirror

$$i_{X4} = i_{X5} = -i_{S1} = -i_{S2} = -i_{X3} \quad (3.76)$$

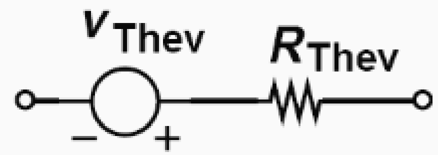
$$r_{out} = \frac{V_X}{i_X} = \frac{V_X}{i_{X1} + i_{X2} + i_{X3} + i_{X4}} = \frac{V_X}{\left(\frac{V_X}{r_{ds4}}\right) + \left(\frac{V_X}{r_{ds2}}\right)} \quad (3.77)$$

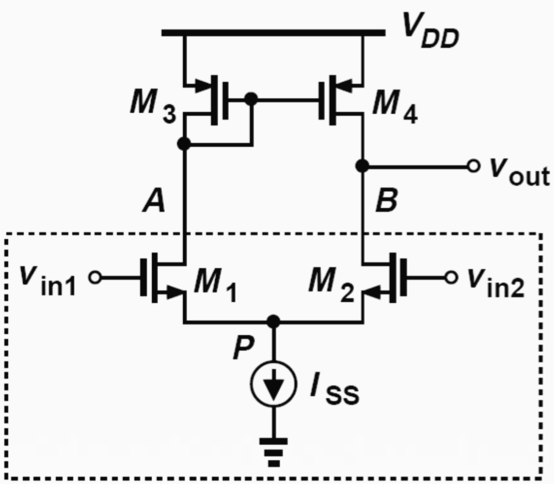
$$r_{out} = r_{ds2} \parallel r_{ds4} \quad (3.78)$$

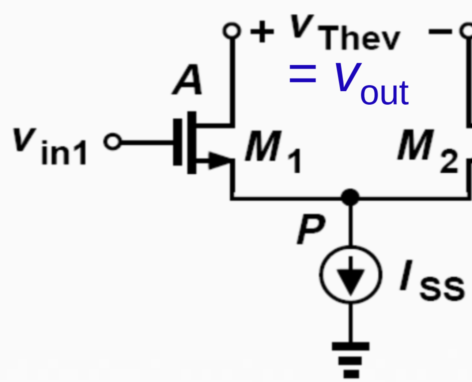
$$A_v = g_m r_{out} = g_{m1}\left(r_{ds2} \parallel r_{ds4}\right) = g_{m1}\left(r_{o2} \parallel r_{o4}\right)$$

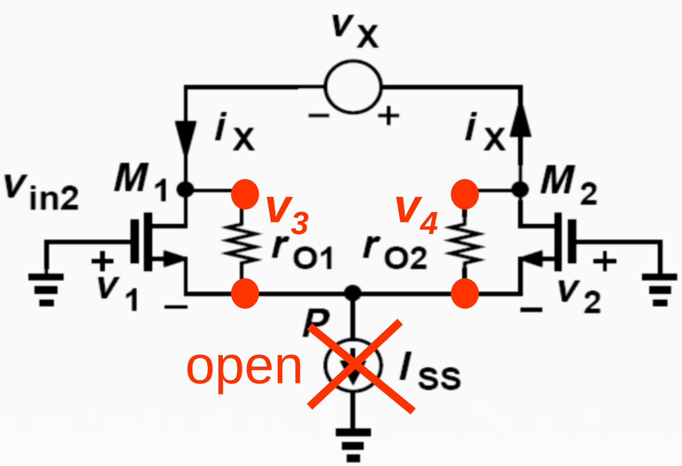
(3.79)

V_{THev} and R_{Thev}









$$\therefore v_{Thev} = -g_m r_{oN}(v_{in1} - v_{in2})$$

$$v_3 + v_4 = v_X$$

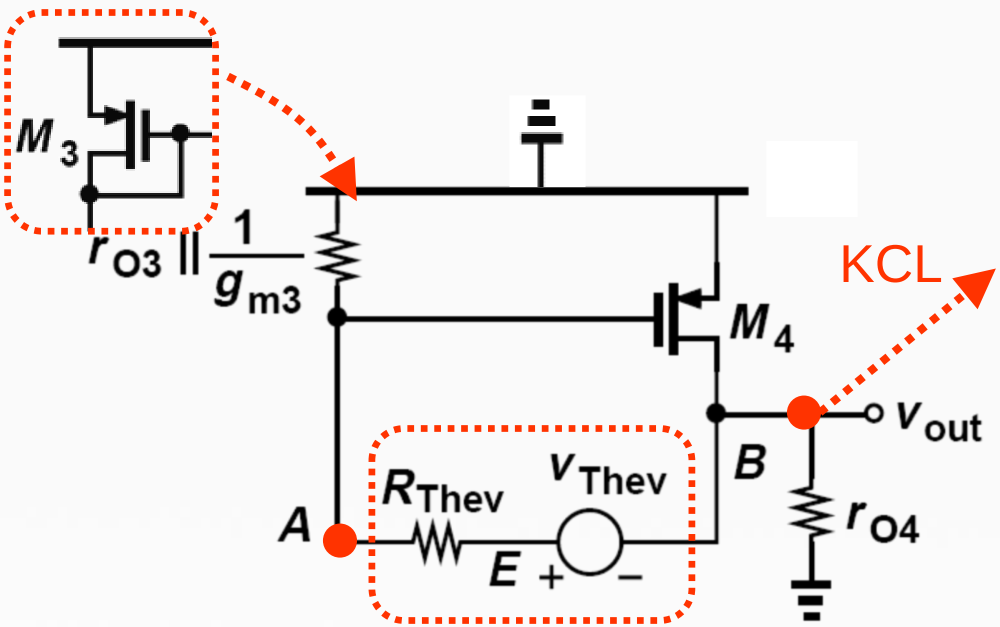
$$(i_X - g_{m1}v_1)r_{O1} + (i_X + g_{m2}v_2)r_{O2} = v_X$$

since $v_1 = v_2,\ g_{m1} = g_{m2}, r_{01} = r_{02} = r_{oN}$

$$i_X r_{oN} + i_X r_{oN} = v_X$$

$$\therefore R_{Thev} = \frac{v_X}{i_X} = 2r_{oN}$$

Simplified Differential Pair with Active Load



$$v_A = \frac{1/g_{m3} \| r_{O3}}{1/g_{m3} \| r_{O3} + R_{Thev}} (v_{out} + v_{Thev})$$

$$-g_{m4}(-v_A) + \frac{v_{out}}{r_{O4}} + \frac{v_{out} + v_{Thev}}{1/g_{m3} \| r_{O3} + R_{Thev}} = 0$$

since $1/g_{m3} << r_{03}, 1/g_{m3} << R_{Thev}$,

$g_{m3} = g_{m4} = g_{mp}, r_{03} = r_{04} = r_{oP}$

$$\frac{2}{R_{Thev}}(v_{out} + v_{Thev}) + \frac{v_{out}}{r_{oP}} = 0$$

$$v_{out}\left(\frac{1}{r_{oN}} + \frac{1}{r_{oP}}\right) = \frac{g_{mN} r_{oN}(v_{in1} - v_{in2})}{r_{oN}}$$

$$\left\{ \begin{array}{l} v_{Then} = -g_m r_{oN}(v_{in1} - v_{in2}) \\ R_{Thev} = 2 r_{oN} \end{array} \right.$$

$$\therefore \frac{v_{out}}{v_{in1} - v_{in2}} = g_{mN}(r_{oN} \| r_{oP})$$

$$= g_{m1,2}(r_{O1,02} \| r_{O3,04})$$