
Amplificadores Diferenciais

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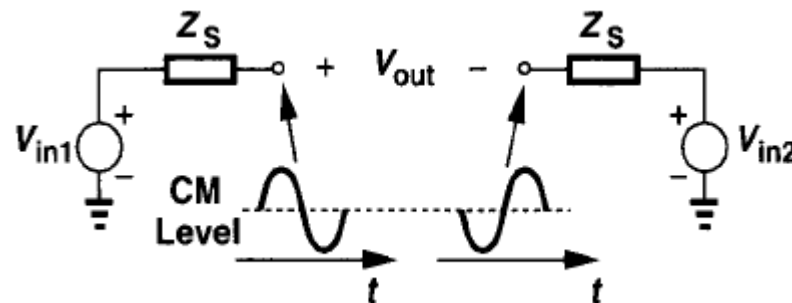
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Amplificadores Diferenciais

- Apresentam diversas vantagens em relação a amplificadores de um ramo:
 - Rejeição de ruído
 - Rejeição de nível dc comum
 - Maior output swing

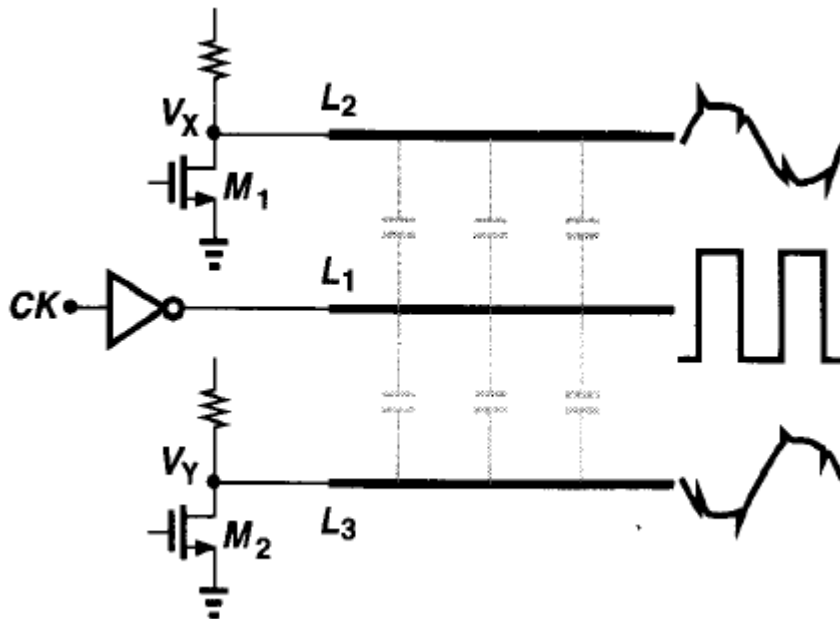
Amplificadores Diferenciais

- Um sinal Single-ended é definido sobre com relação a um potencial fixo, geralmente o terra (ground).
- O par diferenciado é formado por 2 ramos idênticos com sinais de mesma magnitude e opostos em cada ramo e com impedâncias iguais.
- O potencial central no sinal diferencial é chamado de “common-mode”.



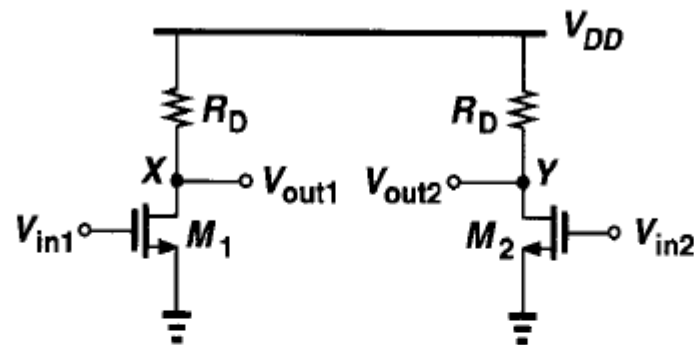
Amplificador Diferencial: rejeição de ruído

- Um ruído na fonte de alimentação, ou até mesmo nas 2 entradas é cancelado. Qualquer sinal não desejado que se manifeste igualmente nos terminais de entrada será cancelado.

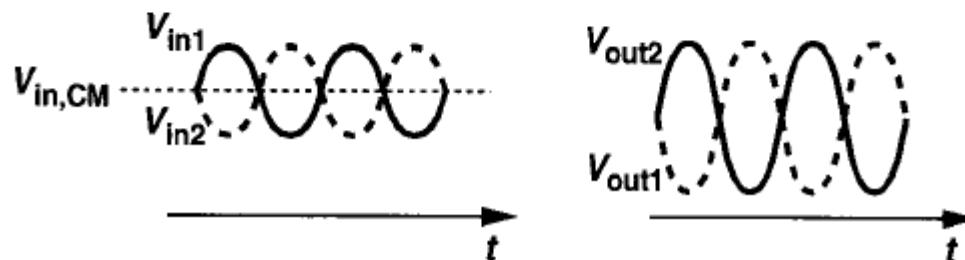


Amplificador Diferencial: maior output swing

- Se a máxima tensão em um ramo é
- $V_{DD} - (V_{GS} - v_{th})$, $V_X - V_Y = 2[V_{DD} - (V_{GS} - V_{th})]$
- Outras vantagens do diferencial: maior linearidade e polarização mais simples.

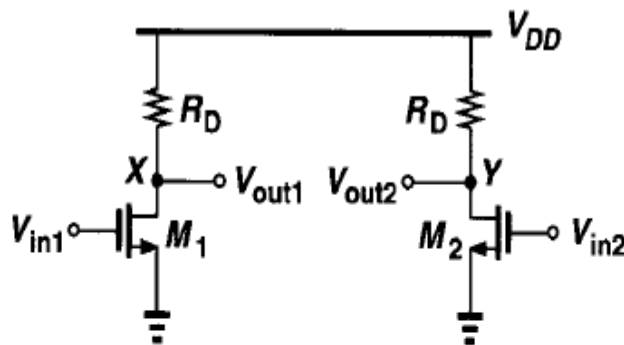


(a)



Amplificador Diferencial: topologia básica

- Amplificador diferencial: 2 amplificadores single-ended **idênticos** para processar as duas fases.
- Alta rejeição ao ruído de fonte, maior output swing – porém alta sensibilidade ao nível CM.



(a)

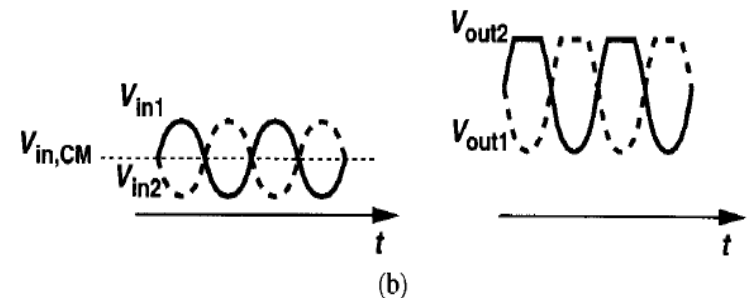
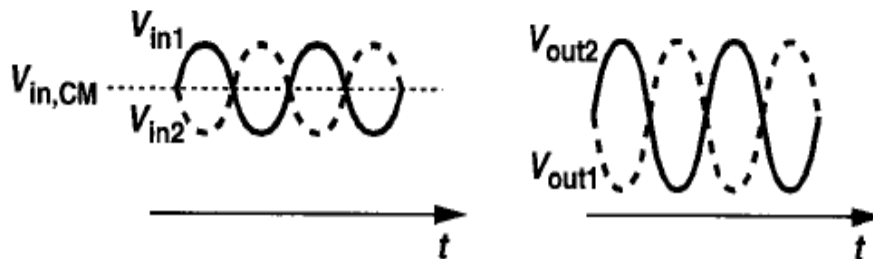
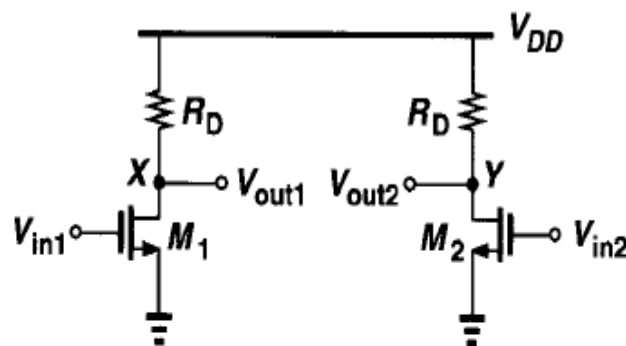


Figure 4.5 (a) Simple differential circuit, (b) illustration of sensitivity to the input common-mode level.

Amplificador Diferencial: topologia básica

- Common-mode (CM) varia \Rightarrow corrente em M1 e M2 variam \Rightarrow transcondutância varia \Rightarrow Output CM varia.
- Low Input CM level – minimum values of V_{in} turn off M1 and M2.



(a)

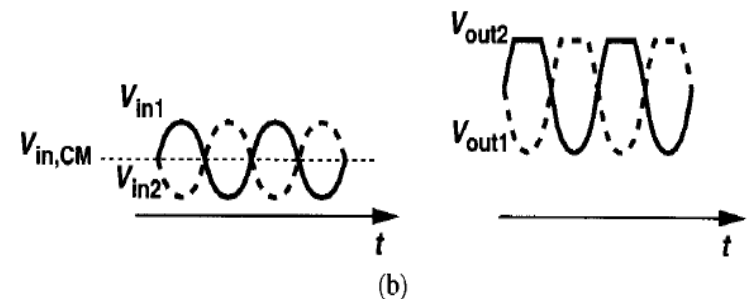
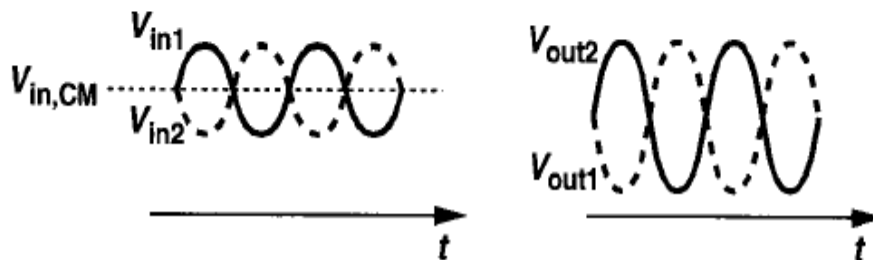
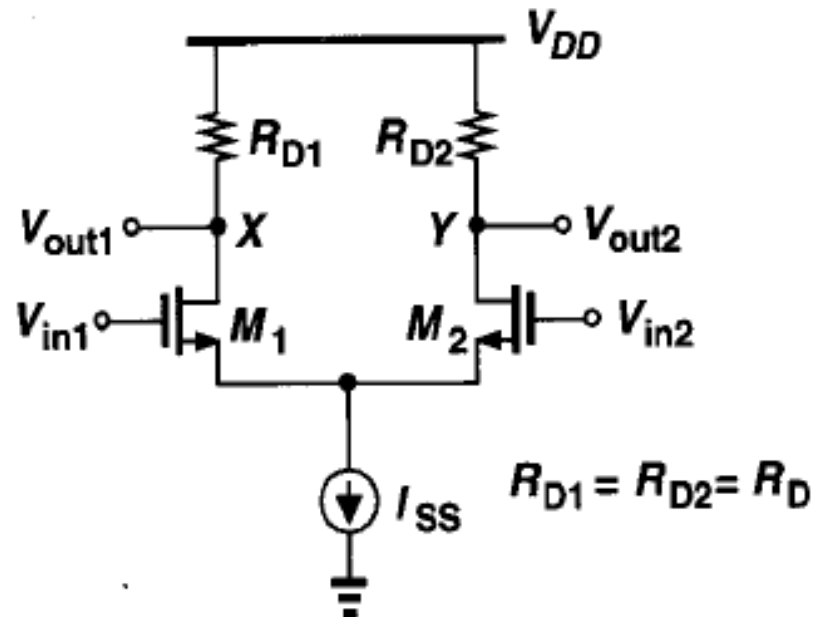


Figure 4.5 (a) Simple differential circuit, (b) illustration of sensitivity to the input common-mode level.

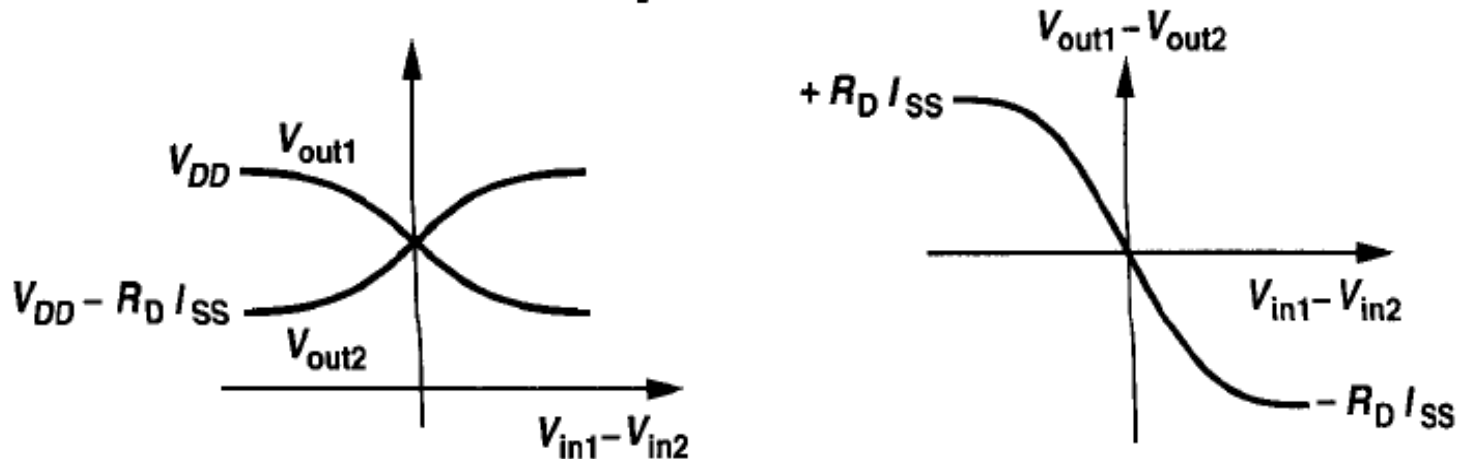
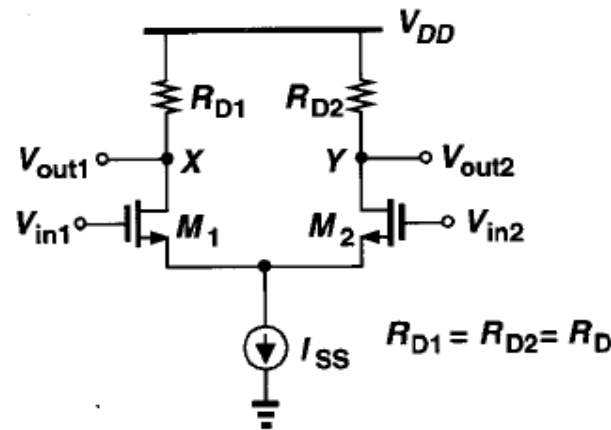
Amplificador Diferencial: topologia básica

- O par diferencial é polarizado por uma fonte de corrente (tail current source) de modo que a soma das correntes ($I_{d1} + I_{d2}$) nos ramos seja constante, assim a saída fica independente do nível comum CM.
- Assim, se $V_{in1} = V_{in2}$, $I_{d1} = I_{d2} = I_{ss}/2$ (independente de $V_{in,CM}$) e $V_{out,CM} = V_{DD} - R_D \cdot I_{ss}/2$



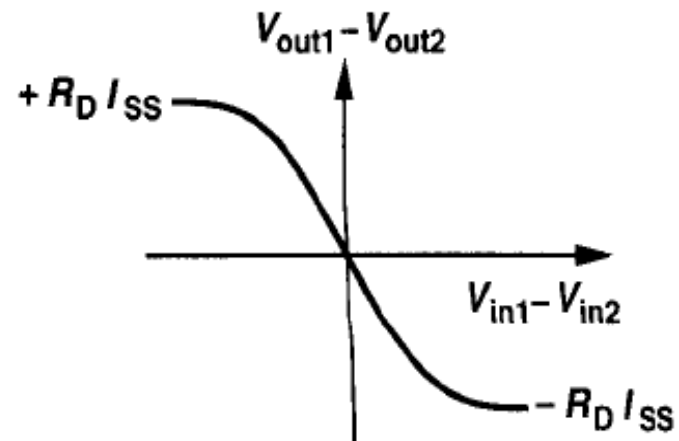
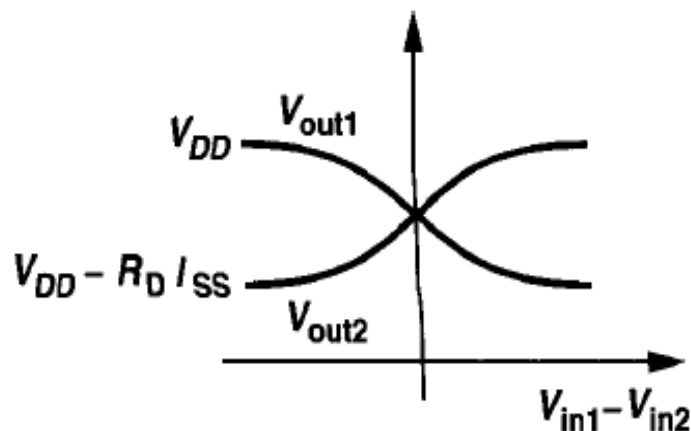
Amplificador diferencial – análise qualitativa

- Se $V_{in1} \ll V_{in2}$: M1 off, M2 on, $I_{d2} = I_{SS}$
- Assim, os limites da tensão de saída ficam limitados a $|R_D I_{SS}|$



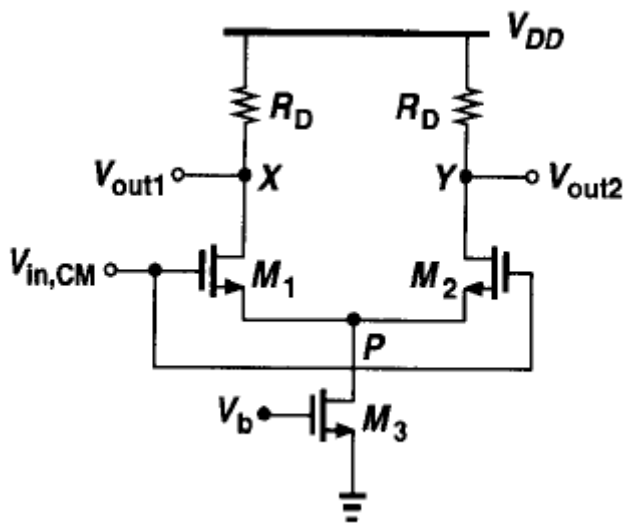
Amplificador diferencial – análise qualitativa

- Os limites da tensão de saída ficam limitados a $|R_D I_{SS}|$ e independentes do nível CM da entrada
- O ganho é máximo (slope $V_{out1}-V_{out2}$ x $V_{in1}-V_{in2}$) quando $V_{in1}=V_{in2}$. O ganho tende a zero quando $V_{in1}-V_{in2}$ cresce.
- Ou seja, o circuito é menos linear quando Vin swing aumenta.



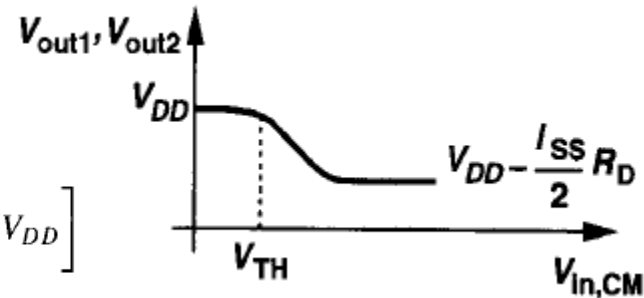
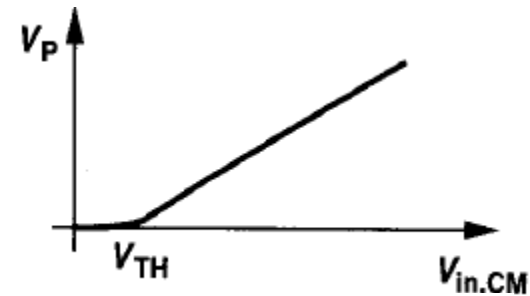
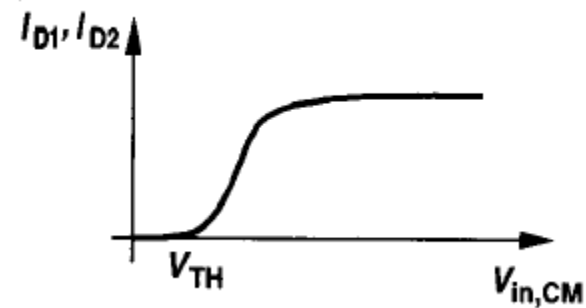
Amplificador diferencial: resposta a nível comum

- As curvas abaixo mostram o efeito do nível CM em cada ramo de saída:



Para manter M1 e M2 em saturação, $V_{in,CM}$ deve ficar entre:

$$V_{GS1} + (V_{GS3} - V_{TH3}) \leq V_{in,CM} \leq \min \left[V_{DD} - R_D \frac{I_{SS}}{2} + V_{TH}, V_{DD} \right]$$



Amplificador diferencial: resposta a nivel comum

Example 4.1

Sketch the small-signal differential gain of a differential pair as a function of the input CM level.

Solution

As shown in Fig. 4.9, the gain begins to increase as $V_{in,CM}$ exceeds V_{TH} . After the tail current source

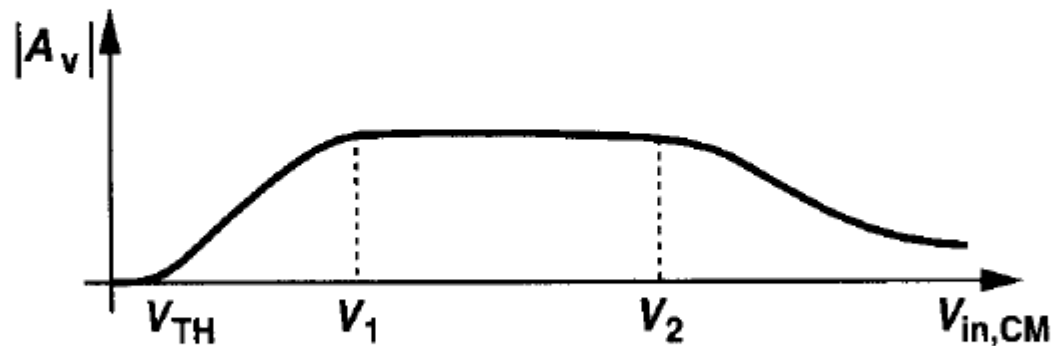
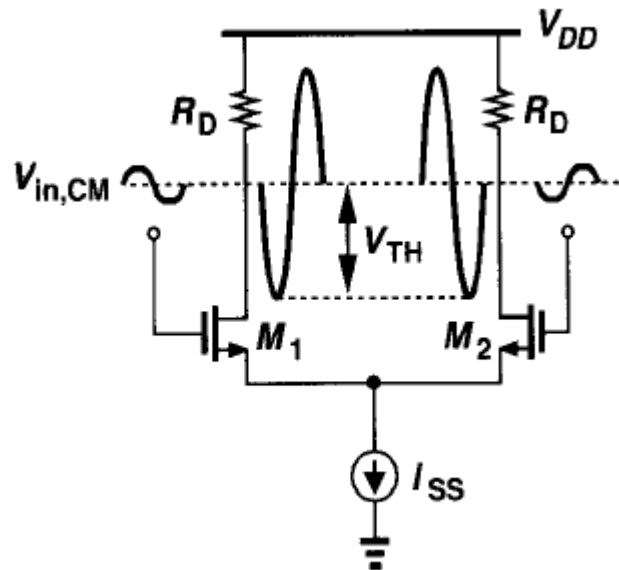


Figure 4.9

enters saturation ($V_{in,CM} = V_1$), the gain remains relatively constant. Finally, if $V_{in,CM}$ is so high that the input transistors enter the triode region ($V_{in,CM} = V_2$), the gain begins to fall.

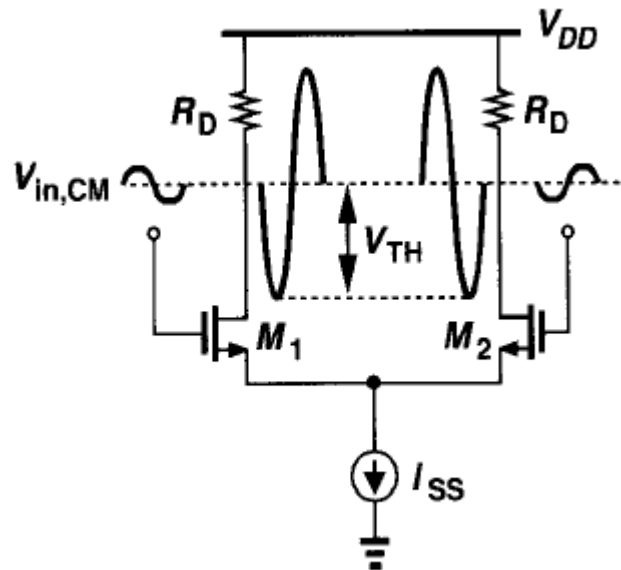
Amplificador diferencial: Output swing

- M1 and M2 to be saturated – each output can go as high as V_{DD} but as low as approximately $V_{in,CM} - V_{th}$.
- The higher the input CM level, the smaller the allowable output swings.



Amplificador diferencial: Output swing

- Para obter um maior output swing, o nível $V_{in,CM}$ deve estar próximo de $R_D I_{SS}/2$, o que impõe um trade-off entre ganho e output swing (o ganho do diff. Pair é função da tensão DC sobre o R_D , se $R_D I_{SS}/2$ é alto, $V_{in,CM}$ deve permanecer próximo de zero).



Amplificador diferencial: análise de grandes sinais

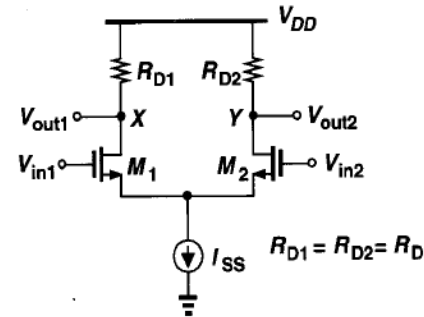
$$V_{out1} = V_{DD} - R_{D1}I_{D1}$$

$$V_{out2} = V_{DD} - R_{D2}I_{D2}$$

$$V_{in1} - V_{in2} = V_{GS1} - V_{GS2}$$

$$V_{out1} - V_{out2} = R_{D2}I_{D2} - R_{D1}I_{D1} = R_D(I_{D2} - I_{D1})$$

$$I_{D1} + I_{D2} = I_{SS}$$



$$(V_{GS} - V_{TH})^2 = \frac{I_D}{\frac{1}{2}\mu_n C_{ox} \frac{W}{L}}$$

$$\frac{1}{2}\mu_n C_{ox} \frac{W}{L} (V_{in1} - V_{in2})^2 - I_{SS} = -2\sqrt{I_{D1}I_{D2}}$$

$$(V_{in1} - V_{in2})^2 = \frac{2}{\mu_n C_{ox} \frac{W}{L}} (I_{SS} - 2\sqrt{I_{D1}I_{D2}})$$

$$V_{GS} = \sqrt{\frac{2I_D}{\mu_n C_{ox} \frac{W}{L}}} + V_{TH}$$

$$(I_{D1} - I_{D2})^2 = -\frac{1}{4} \left(\mu_n C_{ox} \frac{W}{L} \right)^2 (V_{in1} - V_{in2})^4 + I_{SS} \mu_n C_{ox} \frac{W}{L} (V_{in1} - V_{in2})^2$$

$$V_{in1} - V_{in2} = \sqrt{\frac{2I_{D1}}{\mu_n C_{ox} \frac{W}{L}}} - \sqrt{\frac{2I_{D2}}{\mu_n C_{ox} \frac{W}{L}}}$$

$$I_{D1} - I_{D2} = \frac{1}{2}\mu_n C_{ox} \frac{W}{L} (V_{in1} - V_{in2}) \sqrt{\frac{4I_{SS}}{\mu_n C_{ox} \frac{W}{L}} - (V_{in1} - V_{in2})^2}$$

Amplificador diferencial: análise de grandes sinais

$$V_{out1} = V_{DD} - R_{D1}I_{D1}$$

$$V_{out2} = V_{DD} - R_{D2}I_{D2}$$

$$V_{in1} - V_{in2} = V_{GS1} - V_{GS2}$$

$$(V_{GS} - V_{TH})^2 = \frac{I_D}{\frac{1}{2}\mu_n C_{ox} \frac{W}{L}}$$

$$V_{GS} = \sqrt{\frac{2I_D}{\mu_n C_{ox} \frac{W}{L}}} + V_{TH}$$

$$V_{in1} - V_{in2} = \sqrt{\frac{2I_{D1}}{\mu_n C_{ox} \frac{W}{L}}} - \sqrt{\frac{2I_{D2}}{\mu_n C_{ox} \frac{W}{L}}}$$

$$V_{out1} - V_{out2} = R_{D2}I_{D2} - R_{D1}I_{D1} = R_D(I_{D2} - I_{D1})$$

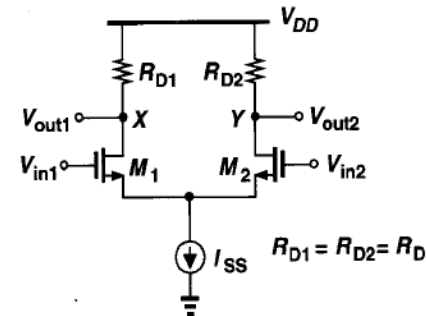
$$I_{D1} + I_{D2} = I_{SS}$$

$$(V_{in1} - V_{in2})^2 = \frac{2}{\mu_n C_{ox} \frac{W}{L}} (I_{SS} - 2\sqrt{I_{D1}I_{D2}})$$

$$\frac{1}{2}\mu_n C_{ox} \frac{W}{L} (V_{in1} - V_{in2})^2 - I_{SS} = -2\sqrt{I_{D1}I_{D2}}$$

Squaring the two sides again and noting that $4I_{D1}I_{D2} = (I_{D1} + I_{D2})^2 - (I_{D1} - I_{D2})^2 = I_{SS}^2 - (I_{D1} - I_{D2})^2$, we arrive at

$$(I_{D1} - I_{D2})^2 = -\frac{1}{4} \left(\mu_n C_{ox} \frac{W}{L} \right)^2 (V_{in1} - V_{in2})^4 + I_{SS} \mu_n C_{ox} \frac{W}{L} (V_{in1} - V_{in2})^2$$



$$I_{D1} - I_{D2} = \frac{1}{2}\mu_n C_{ox} \frac{W}{L} (V_{in1} - V_{in2}) \sqrt{\frac{4I_{SS}}{\mu_n C_{ox} \frac{W}{L}} - (V_{in1} - V_{in2})^2}$$

Amplificador diferencial: ganho

$$I_{D1} - I_{D2} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in1} - V_{in2}) \sqrt{\frac{4I_{SS}}{\mu_n C_{ox} \frac{W}{L}} - (V_{in1} - V_{in2})^2}$$

As expected, $I_{D1} - I_{D2}$ is an odd function of $V_{in1} - V_{in2}$, falling to zero for $V_{in1} = V_{in2}$.

$$G_m = \frac{\partial \Delta I_D}{\partial \Delta V_{in}} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} \frac{\frac{4I_{SS}}{\mu_n C_{ox} W/L} - 2\Delta V_{in}^2}{\sqrt{\frac{4I_{SS}}{\mu_n C_{ox} W/L} - \Delta V_{in}^2}}$$

$$\Delta V_{in} = 0, G_m = \sqrt{\mu_n C_{ox} (W/L) I_{SS}}$$

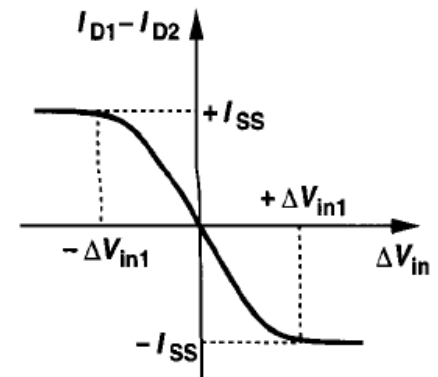
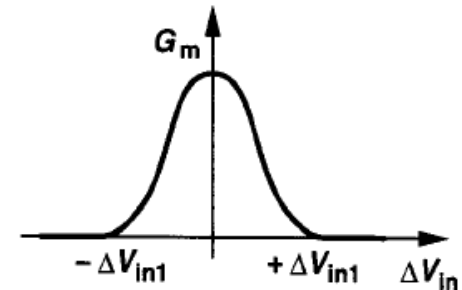
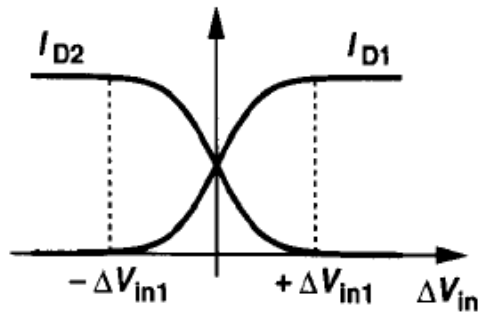
$$V_{out1} - V_{out2} = R_D \Delta I = R_D G_m \Delta V_{in},$$

$$|A_v| = \sqrt{\mu_n C_{ox} \frac{W}{L} I_{SS}} R_D$$

Ganho do
circuito em
equilíbrio

$$\Delta V_{in} = \sqrt{2I_{SS}/(\mu_n C_{ox} W/L)}, G_m = 0,$$

Este é o máximo
diferencial ao qual o
cricuito responde



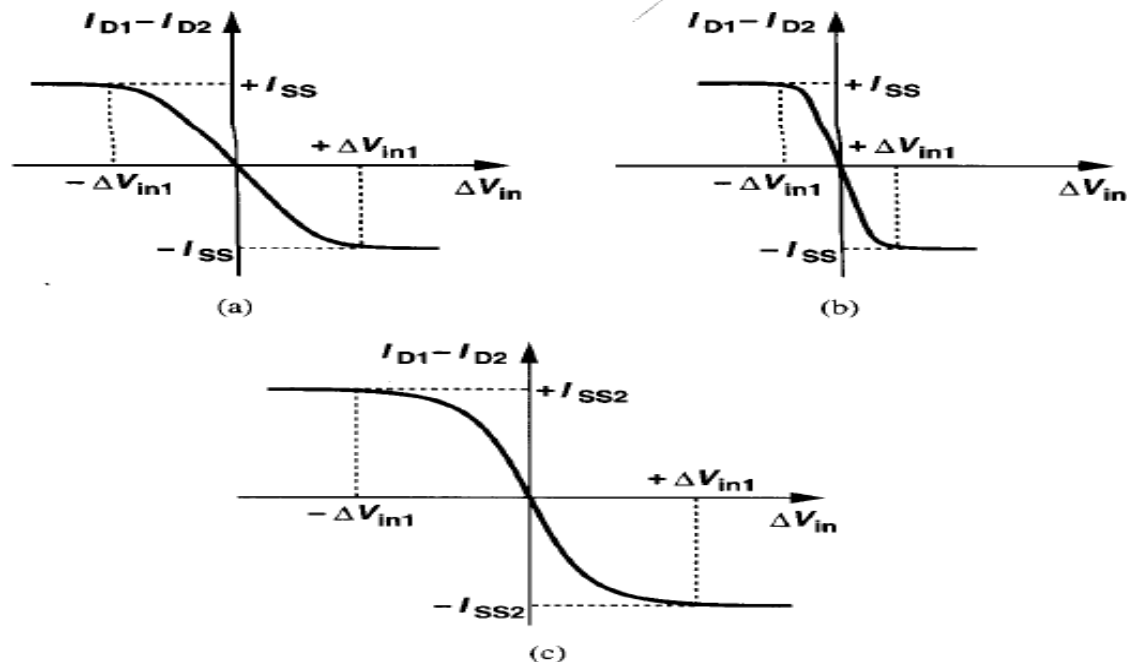
Amplificador diferencial: ganho

Example 4.2

Plot the input-output characteristic of a differential pair as the device width and the tail current vary.

Solution

Consider the characteristic shown in Fig. 4.13(a). As W/L increases, ΔV_{in1} decreases, narrowing the input range across which both devices are on [Fig. 4.13(b)]. As I_{SS} increases, both the input range and the output current swing increase [Fig. 4.13(c)]. Intuitively, we expect the circuit to become more linear as I_{SS} increases or W/L decreases.



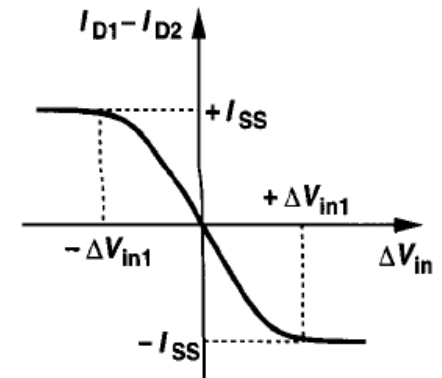
Amplificador diferencial: ganho

Este é o máximo diferencial ao qual o circuito responde

$$\Delta V_{in1} = \sqrt{\frac{2I_{SS}}{\mu_n C_{ox} \frac{W}{L}}}, \quad G_m = 0.$$

For a zero differential input, $I_{D1} = I_{D2} = I_{SS}/2$,

$$(V_{GS} - V_{TH})_{1,2} = \sqrt{\frac{I_{SS}}{\mu_n C_{ox} \frac{W}{L}}}.$$



Thus, the equilibrium overdrive is equal to $\Delta V_{in1} / \sqrt{2}$.

$$\uparrow \Delta V_{in} (\uparrow \text{linearidade}) \Rightarrow \uparrow (V_{gs} - V_{th})_{1,2} \Rightarrow \downarrow \frac{W}{L} (I_{ss} \rightarrow cte) \Rightarrow \downarrow g_m$$

Trade-off Linearidade x Ganho

Amplificador diferencial: ganho

- Supondo M1 e M2 operando em saturação:

$$|A_v| = \sqrt{\mu_n C_{ox} \frac{W}{L} I_{SS} R_D} \quad I_{d1} = I_{d2} = \frac{I_{SS}}{2} \rightarrow |A_v| = g_{m1,2} \cdot R_D$$

- Ganho do diff. pair X Common-source (CS):

Para a mesma corrente de polarização I_{SS} :

$$g_{m_{diff.pair}} = \sqrt{\mu_n C_{ox} \frac{W}{L} I_{SS}}$$

$$g_{m_{CS}} = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_{SS}}$$

$$g_{m_{diff.pair}} = \frac{g_{m_{CS}}}{\sqrt{2}}$$

O par diferencial tem o mesmo ganho que um estágio CS, com o dobro de corrente de polarização

Amplificador diferencial: small-signal

- Método I - Superposição

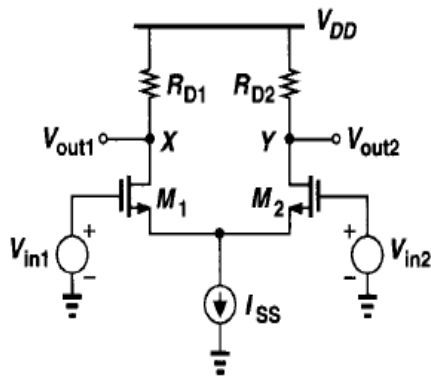


Figure 4.14 Differential pair with small-signal inputs.

$$R_S = 1/g_{m2}$$

$$\frac{V_X}{V_{in1}} = \frac{-R_D}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}}}$$

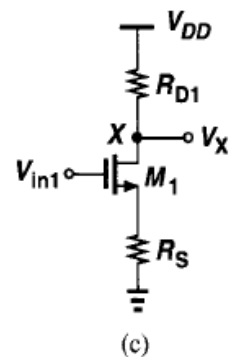
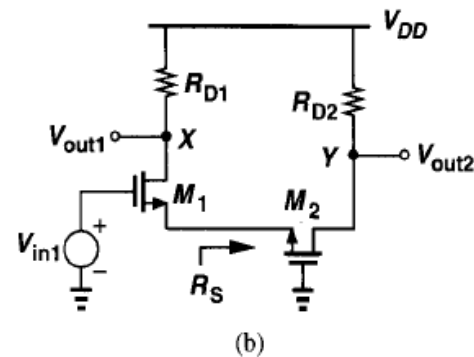
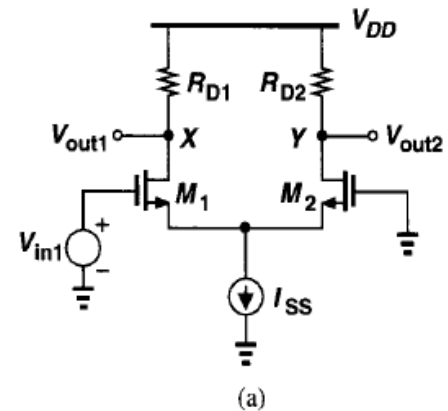


Figure 4.15 (a) Differential pair sensing one input signal, (b) circuit of (a) viewed as a CS stage degenerated by M_2 , (c) equivalent circuit of (b).

Amplificador diferencial: small-signal

Método I - Superposição

To calculate V_Y , we note that M_1 drives M_2 as a source follower and replace V_{in1} and M_1 by a Thevenin equivalent (Fig. 4.16): the Thevenin voltage $V_T = V_{in1}$ and the resistance $R_T = 1/g_{m1}$. Here, M_2 operates as a common-gate stage, exhibiting a gain equal to

$$\frac{V_Y}{V_{in1}} = \frac{R_D}{\frac{1}{g_{m2}} + \frac{1}{g_{m1}}}$$

$$(V_X - V_Y)|_{\text{Due to } V_{in1}} = \frac{-2R_D}{\frac{1}{g_{m1}} + \frac{1}{g_{m2}}} V_{in1},$$

$$g_{m1} = g_{m2} = g_m$$

$$(V_X - V_Y)|_{\text{Due to } V_{in1}} = -g_m R_D V_{in1}.$$

By virtue of symmetry, the effect of V_{in2} at X and Y is identical to that of V_{in1} except for a change in the polarities:

$$(V_X - V_Y)|_{\text{Due to } V_{in2}} = g_m R_D V_{in2}.$$

$$\frac{(V_X - V_Y)_{tot}}{V_{in1} - V_{in2}} = -g_m R_D.$$

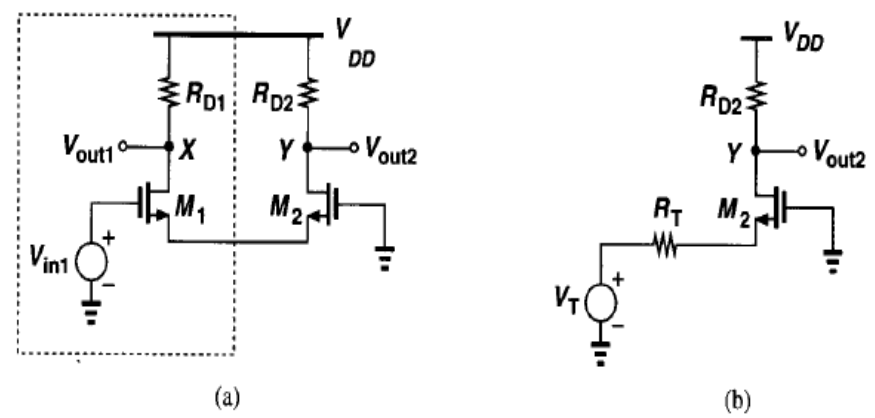


Figure 4.16 Replacing M_1 by a Thevenin equivalent.

Se a saída é “single-ended”: o ganho é a metade

Amplificador diferencial: small-signal

Example 4.3

In the circuit of Fig. 4.17, M_2 is twice as wide as M_1 . Calculate the small-signal gain if the bias values of V_{in1} and V_{in2} are equal.

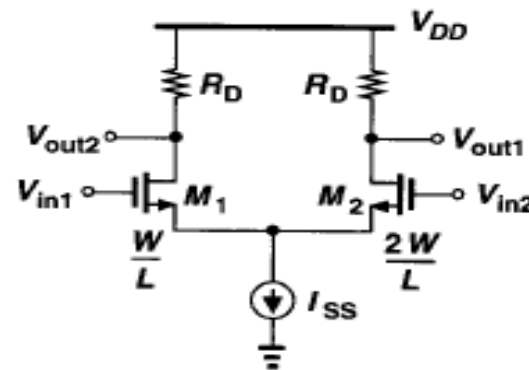


Figure 4.17

Solution

If the gates of M_1 and M_2 are at the same dc potential, then $V_{GS1} = V_{GS2}$ and $I_{D2} = 2I_{D1} = 2I_{SS}/3$. Thus, $g_{m1} = \sqrt{2\mu_n C_{ox}(W/L)I_{SS}/3}$ and $g_{m2} = \sqrt{2\mu_n C_{ox}(2W/L)2I_{SS}/3} = 2g_{m1}$. Following the same procedure as above, the reader can show that

$$|A_v| = \frac{2R_D}{\frac{1}{g_{m1}} + \frac{1}{2g_{m1}}} \quad (4.20)$$

$$= \frac{4}{3}g_{m1}R_D. \quad (4.21)$$

Note that, for a given I_{SS} , this value is lower than the gain of a symmetric differential pair (with $2W/L$ for each device) [Eq. (4.19)] because g_{m1} is smaller.

Amplificador diferencial: meio-circuito

- Método II – Conceito de “Half circuit”
 - Se os 2 ramos de um par diferencial são idênticos, e as tensões de entrada variam com a mesma magnitude, porém em sinais contrários, a tensão no ponto P não muda, logo os ramos podem ser calculados independentemente.

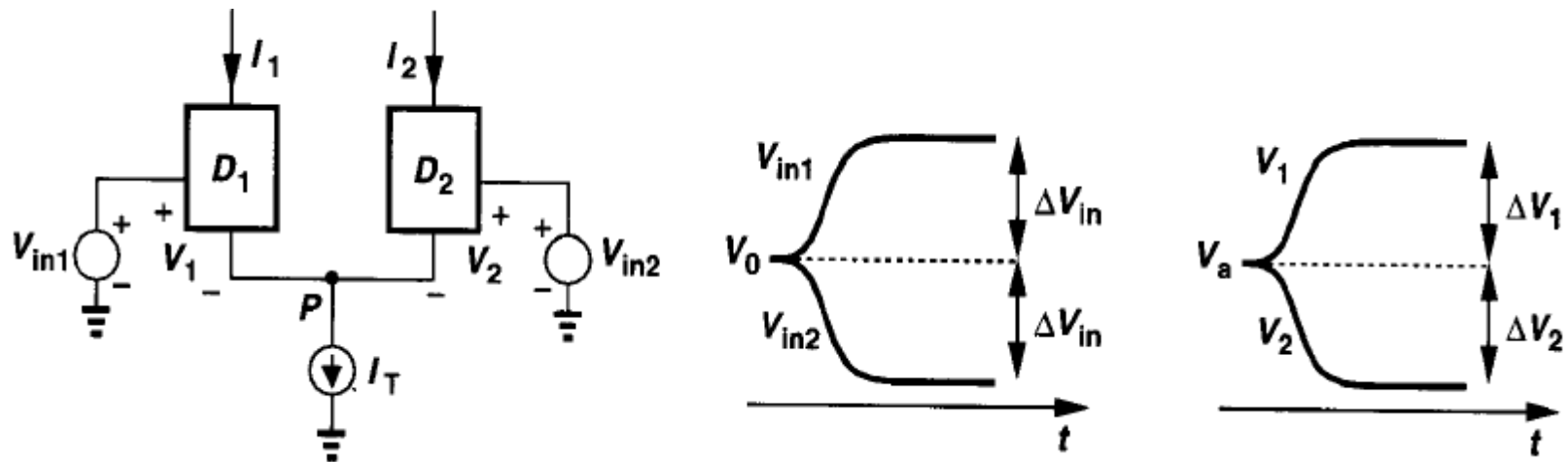
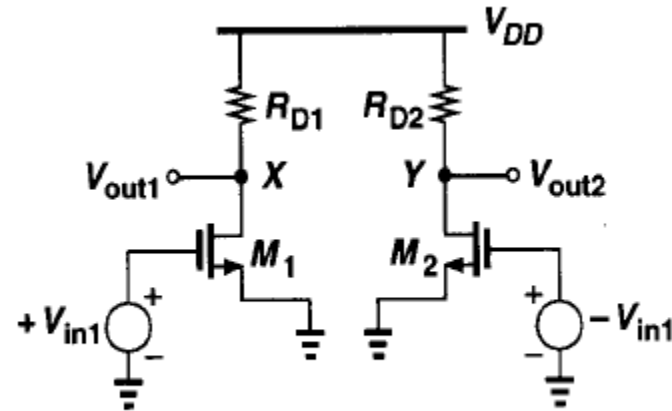
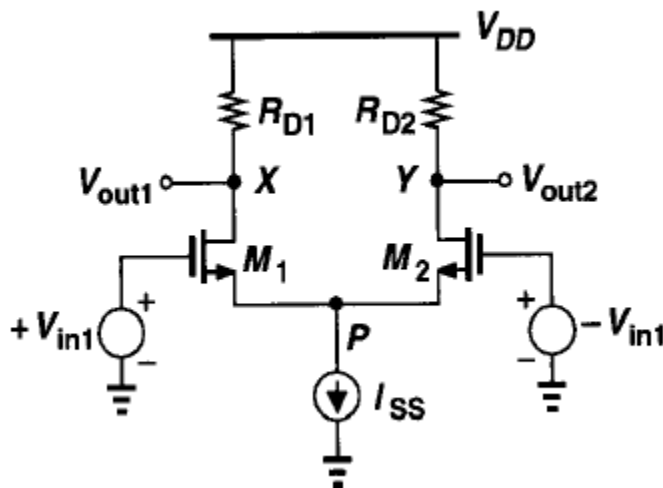


Figure 4.18 Illustration of why node P is a virtual ground.

Amplificador diferencial: modelo de pequenos sinais

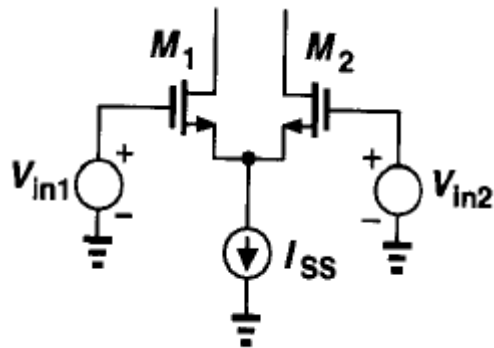
- V_p pode ser considerado como um ac ground.
- Utilizando o lema do meio-circuito, o ganho pode ser calculado por superposição:



- $V_{out1} = -g_{m1}R_d V_{in1}$ $V_{out2} = -g_{m2}R_d V_{in2}$
- $V_{in2} = -V_{in1}$
- $A_v = (V_{out1} - V_{out2}) / (V_{in1} - V_{in2}) = -\mathbf{gmRd}$ ($g_{m1} = g_{m2}$)

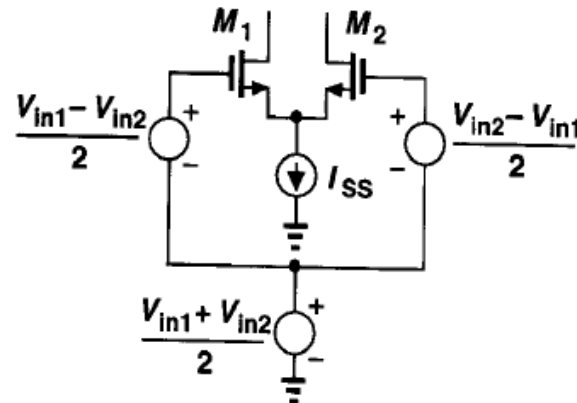
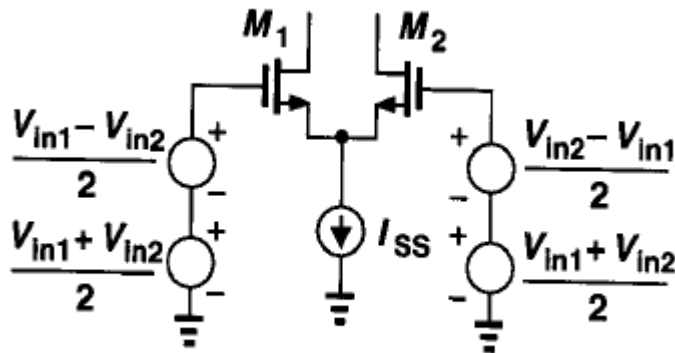
Amplificador diferencial: modelo de pequenos sinais

- Quando se tem níveis CM diferentes em cada entrada, podemos decompor $V_{in1} - V_{in2}$ em uma entrada diferencial e outra DC e aplicar superposição



$$V_{in1} = \frac{V_{in1} - V_{in2}}{2} + \frac{V_{in1} + V_{in2}}{2}$$

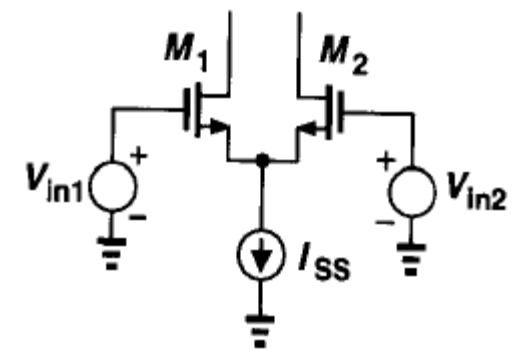
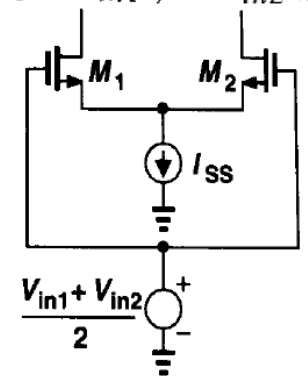
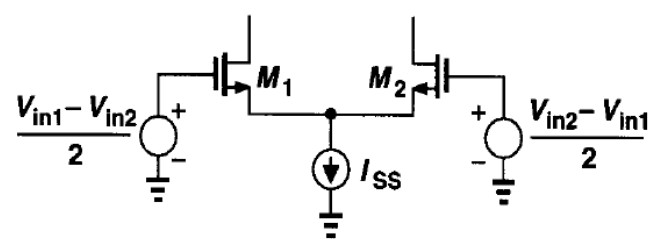
$$V_{in2} = \frac{V_{in2} - V_{in1}}{2} + \frac{V_{in1} + V_{in2}}{2}$$



Amplificador diferencial: modelo de pequenos sinais

Example 4.5

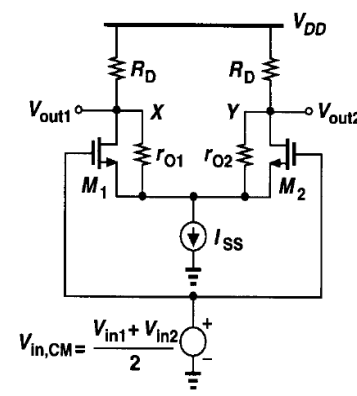
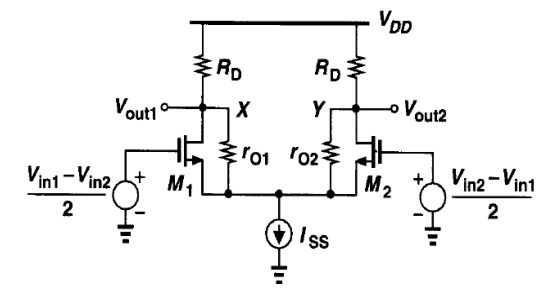
In the circuit of Fig. 4.20(a), calculate V_X and V_Y if $V_{in1} \neq -V_{in2}$ and $\lambda \neq 0$.



$$V_X = -g_m(R_D \parallel r_{O1}) \frac{V_{in1} - V_{in2}}{2}$$

$$V_Y = -g_m(R_D \parallel r_{O2}) \frac{V_{in2} - V_{in1}}{2}.$$

(b)



$$V_X - V_Y = -g_m(R_D \parallel r_O)(V_{in1} - V_{in2}),$$

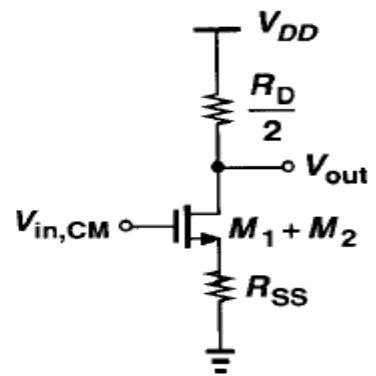
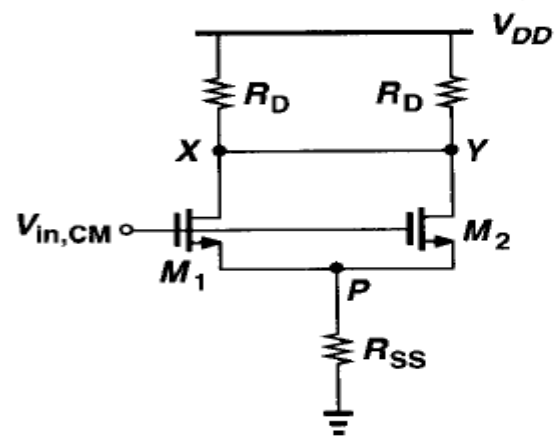
For common-mode operation, the circuit reduces to that in Fig. 4.24(b). How much do V_X and V_Y change as $V_{in,CM}$ changes? If the circuit is fully symmetric and I_{SS} an ideal current source, the current drawn by M_1 and M_2 from R_{D1} and R_{D2} is exactly equal to $I_{SS}/2$ and independent of $V_{in,CM}$. Thus, V_X and V_Y experience no change as $V_{in,CM}$ varies. Interestingly, the circuit simply amplifies the difference between V_{in1} and V_{in2} while eliminating the effect of $V_{in,CM}$.

Amplificador diferencial: Resposta ao modo comum

– impedância finita da fonte de corrente

- Um importante característica do diff. Pair é a habilidade de rejeitar as variações de CM.
- Em condições reais, não se consegue uma impedância infinita da fonte de corrente de polarização, o que provoca uma alteração no ganho do amplificador. Chamamos de “Acm” a variação do ganho devido ao nível CM

$$\uparrow V_{IN,CM} \Rightarrow \uparrow V_p \Rightarrow \uparrow Id_{1,2} \Rightarrow \downarrow V_x, V_y$$



$$A_{v,CM} = \frac{V_{out}}{V_{in,CM}}$$

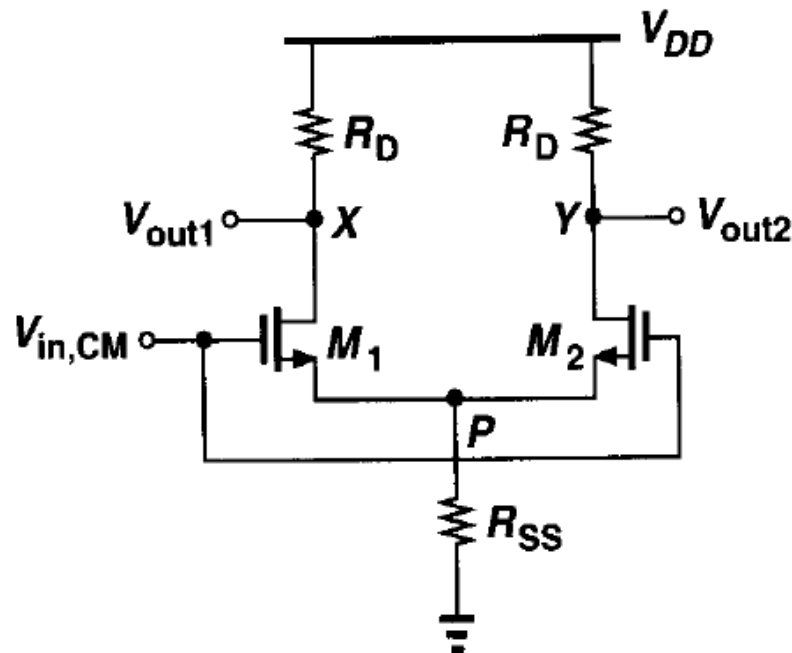
$$= - \frac{R_D/2}{1/(2g_m) + R_{SS}}$$

- Variação de CM, varia a corrente de polarização (Iss) , e assim varia o ganho e limita o “output voltage swing”

Amplificador diferencial: Rejeição de modo comum

- impedância finita da fonte de corrente

- Variações no CM de entrada
 - > Altera pontos de polarização (I_{SS})
 - > Altera o ganho de pequeno sinal
 - > Limita o “output voltage swings”



Amplificador diferencial: Rejeição de modo comum

Example 4.6

The circuit of Fig. 4.26 uses a resistor rather than a current source to define a tail current of 1 mA.

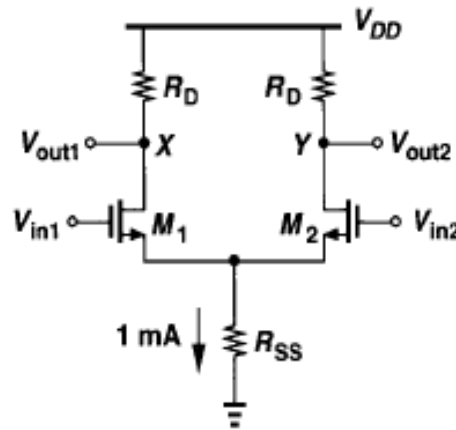


Figure 4.26

Assume $(W/L)_{1,2} = 25/0.5$, $\mu_n C_{ox} = 50 \mu\text{A/V}^2$, $V_{TH} = 0.6 \text{ V}$, $\lambda = \gamma = 0$, and $V_{DD} = 3 \text{ V}$.

- What is the required input CM for which R_{SS} sustains 0.5 V?
- Calculate R_D for a differential gain of 5.
- What happens at the output if the input CM level is 50 mV higher than the value calculated in (a)?

Solution

- Since $I_{D1} = I_{D2} = 0.5 \text{ mA}$, we have

$$V_{GS1} = V_{GS2} = \sqrt{\frac{2I_{D1}}{\mu_n C_{ox} \frac{W}{L}}} + V_{TH} \quad (4.29)$$

$$= 1.23 \text{ V}. \quad (4.30)$$

Thus, $V_{in,CM} = V_{GS1} + 0.5 \text{ V} = 1.73 \text{ V}$. Note that $R_{SS} = 500 \Omega$.

Amplificador diferencial: Rejeição de modo comum

(b) The transconductance of each device is $g_m = \sqrt{2\mu_n C_{ox}(W/L)I_{D1}} = 1/(632 \Omega)$, requiring $R_D = 3.16 \text{ k}\Omega$ for a gain of 5.

Note that the output bias level is equal to $V_{DD} - I_{D1}R_D = 1.42 \text{ V}$. Since $V_{in,CM} = 1.73 \text{ V}$ and $V_{TH} = 0.6 \text{ V}$, the transistors are 290 mV away from the triode region.

(c) If $V_{in,CM}$ increases by 50 mV, the equivalent circuit of Fig. 4.25(c) suggests that V_X and V_Y drop by

$$|\Delta V_{X,Y}| = \Delta V_{in,CM} \frac{R_D/2}{R_{SS} + 1/(2g_m)} \quad (4.31)$$

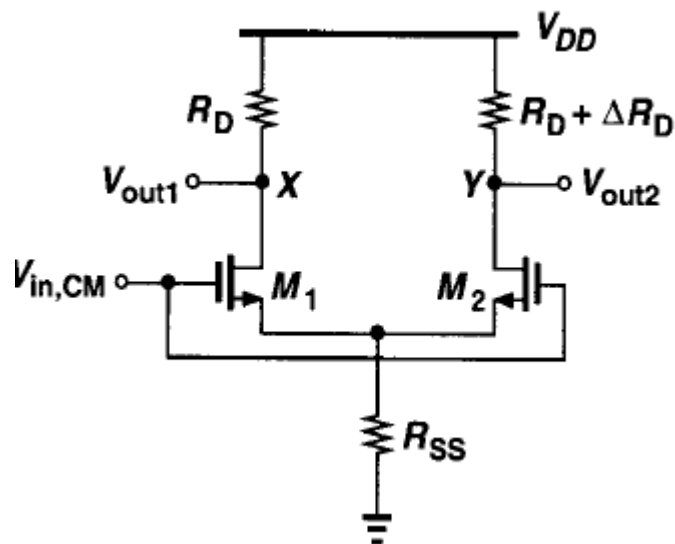
$$= 50 \text{ mV} \times 1.94 \quad (4.32)$$

$$= 96.8 \text{ mV}. \quad (4.33)$$

Now, M_1 and M_2 are only 143 mV away from the triode region because the input CM level has increased by 50 mV and the output CM level has decreased by 96.8 mV.

Amplificador diferencial: resposta ao modo comum

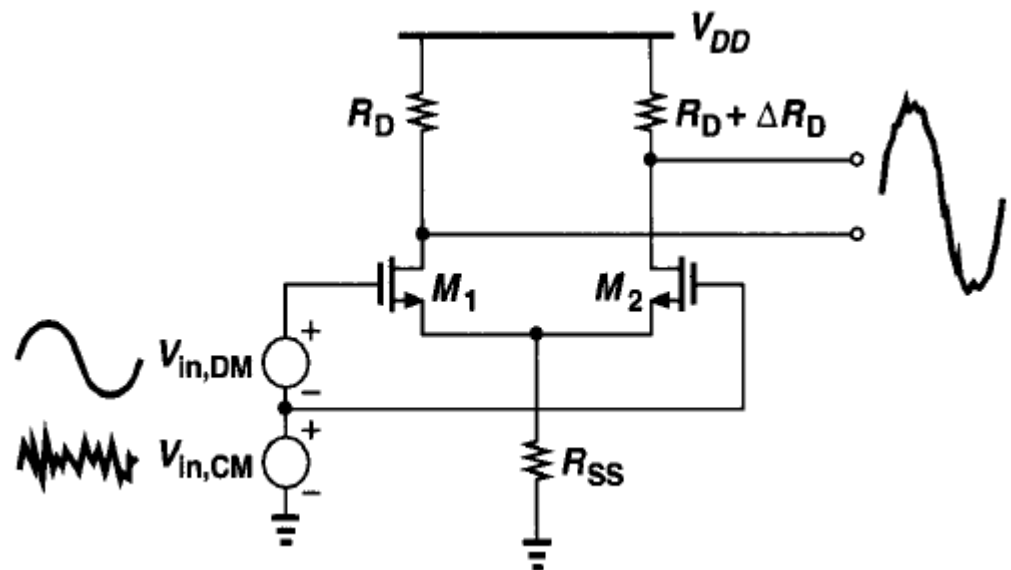
– diferença de resistores



$$\Delta V_X = -\Delta V_{in,CM} \frac{g_m}{1 + 2g_m R_{SS}} R_D$$

$$\Delta V_Y = -\Delta V_{in,CM} \frac{g_m}{1 + 2g_m R_{SS}} (R_D + \Delta R_D)$$

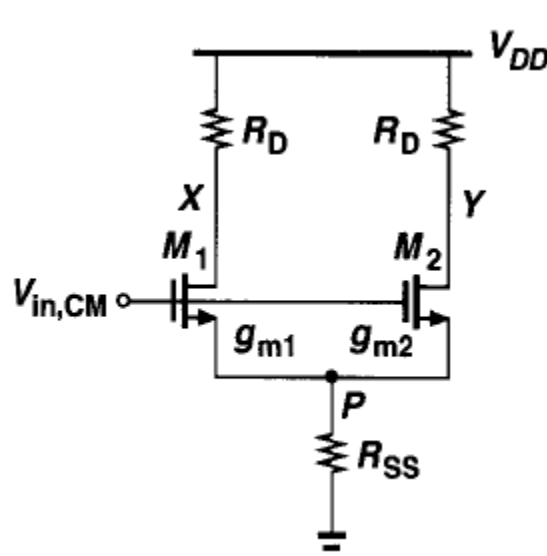
A variação no modo comum causa uma variação na saída diferencial devido à diferenças no valor de R_D



Amplificador diferencial: resposta ao modo comum

– diferença de resistores

- Caso haja uma diferença entre os transistores, aparecerá uma componente diferencial devido ao Modo comum chamada de “Acm-dm” (Resposta diferencial devido ao modo comum)



$$I_{D1} = g_{m1}(V_{in,CM} - V_P)$$

$$I_{D2} = g_{m2}(V_{in,CM} - V_P)$$

$$(g_{m1} + g_{m2})(V_{in,CM} - V_P)R_{SS} = V_P$$

$$V_P = \frac{(g_{m1} + g_{m2})R_{SS}}{(g_{m1} + g_{m2})R_{SS} + 1} V_{in,CM}$$

$$V_X = -g_{m1}(V_{in,CM} - V_P)R_D$$

$$= \frac{-g_{m1}}{(g_{m1} + g_{m2})R_{SS} + 1} R_D V_{in,CM}$$

$$V_Y = -g_{m2}(V_{in,CM} - V_P)R_D$$

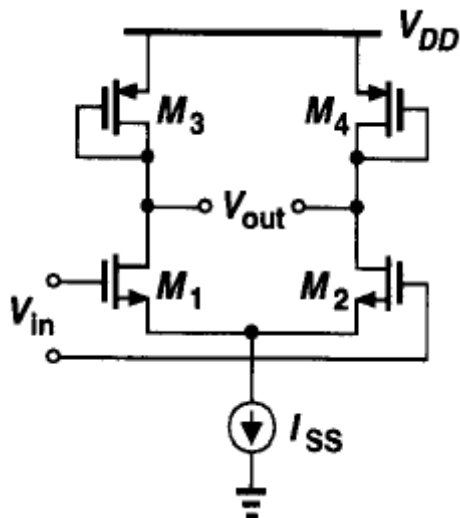
$$= \frac{-g_{m2}}{(g_{m1} + g_{m2})R_{SS} + 1} R_D V_{in,CM}$$

$$V_X - V_Y = -\frac{g_{m1} - g_{m2}}{(g_{m1} + g_{m2})R_{SS} + 1} R_D V_{in,CM}$$

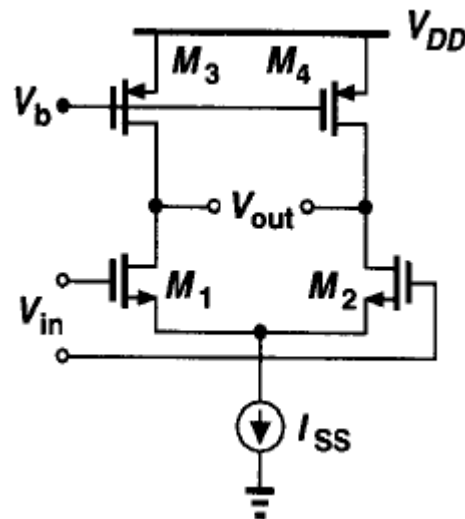
$$A_{CM-DM} = -\frac{\Delta g_m R_D}{(g_{m1} + g_{m2})R_{SS} + 1}$$

Amplificador Diferencial: carga MOS

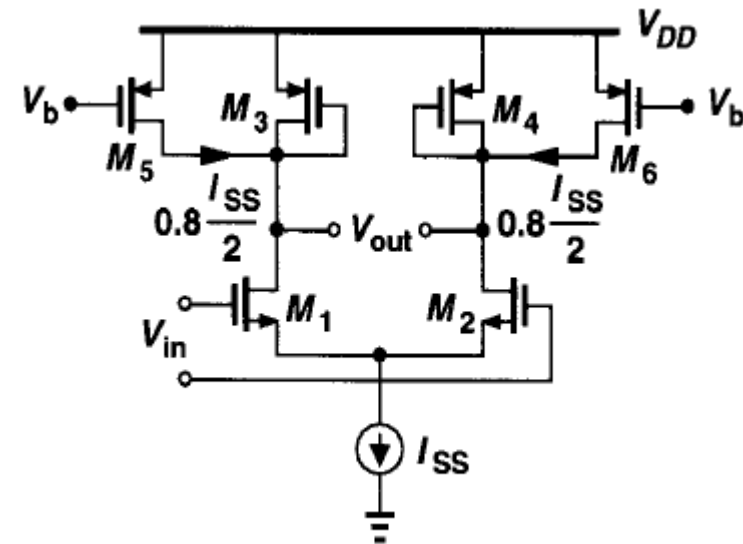
- Os resistores utilizados em um par diferencial podem ser substituídos por um P-MOS tanto diode-connected quanto como fonte de corrente ou uma combinação de ambos.



$$A_v \approx -\sqrt{\frac{\mu_n(W/L)_N}{\mu_p(W/L)_P}}$$



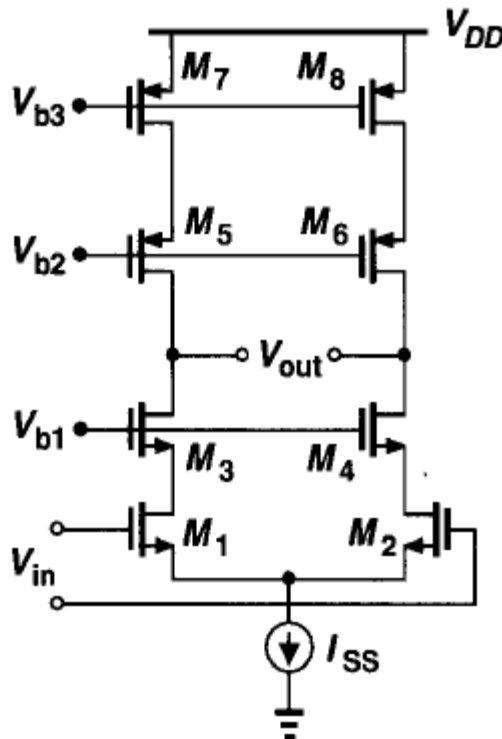
$$A_v = -g_{mN}(r_{ON} \parallel r_{OP})$$



Sendo o ganho dos amplificador proporcional a $1/g_{mp}$, reduzimos a corrente que passa nos P-FETs diode-connected para reduzir g_{mp}

Amplificador diferencial: Cascode

- Para aumentar o ganho do amplificador, podemos colocar cargas cascode, porém com menor limite de tensão:



$$|A_v| \approx g_{m1} [(g_{m3} r_{o3} r_{o1}) \parallel (g_{m5} r_{o5} r_{o7})].$$