Universidade de Brasília

Faculdade UnB Gama

Projeto de Circuitos Eletrônicos Integrados 2

Amplificadores Operacionais Avançados
Folded Cascode

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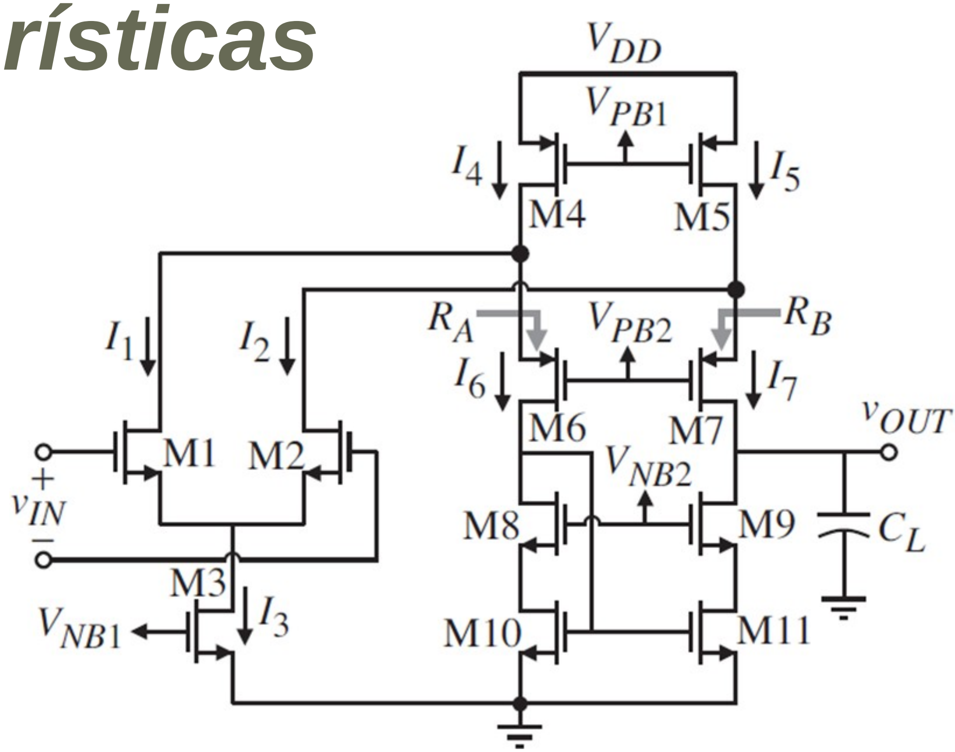
Características



- Auto compensado
- Bom PSRR
- Bom ICMR
- I4 e I5 devem ser projetados de tal maneira que I6 e I7 nunca sejam 0 (Ex. I4=I5=1.5*I3)

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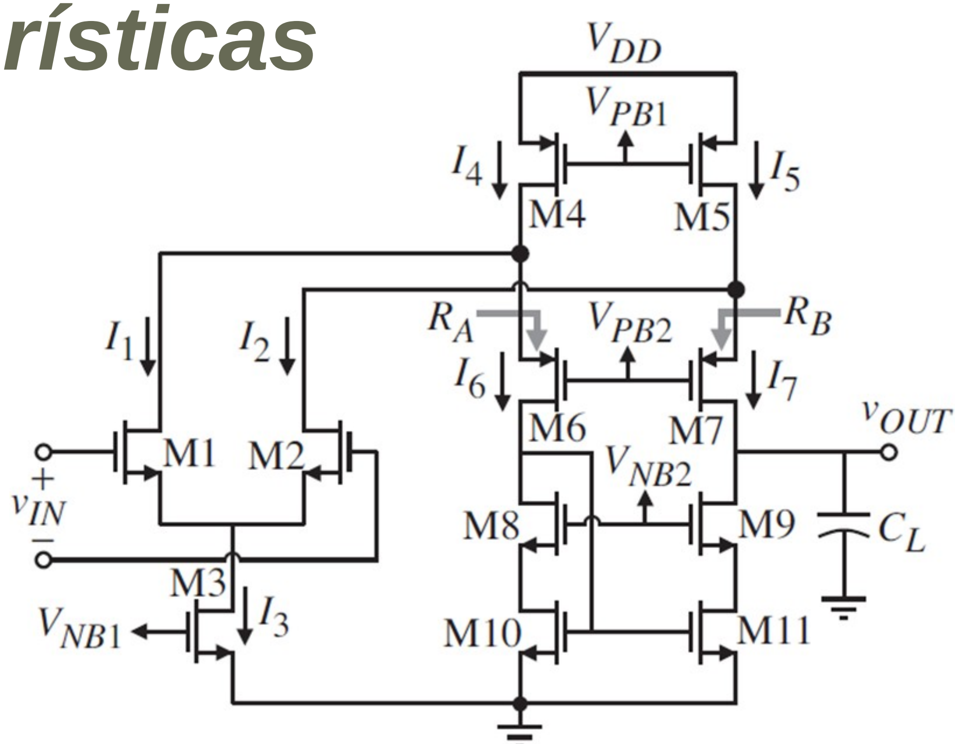

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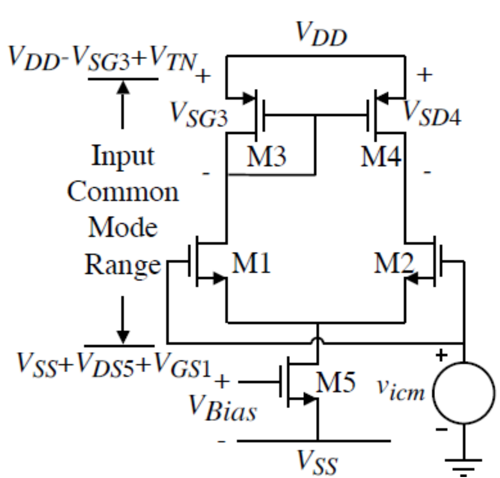
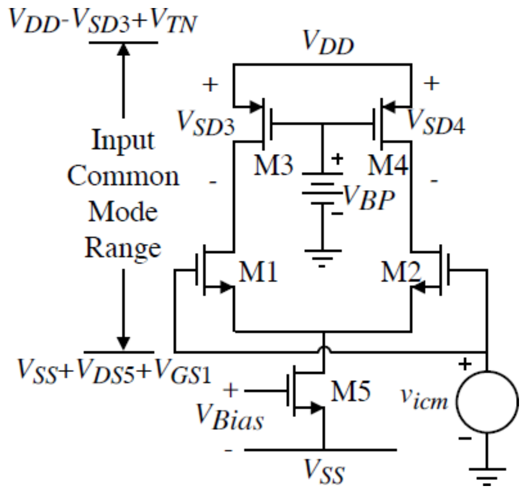
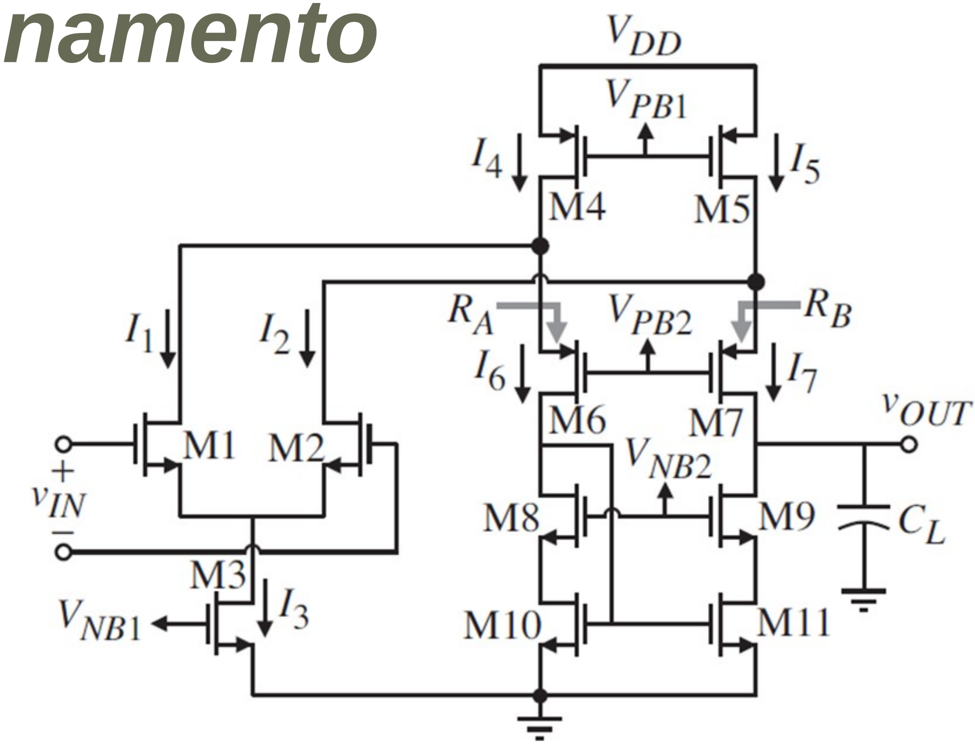
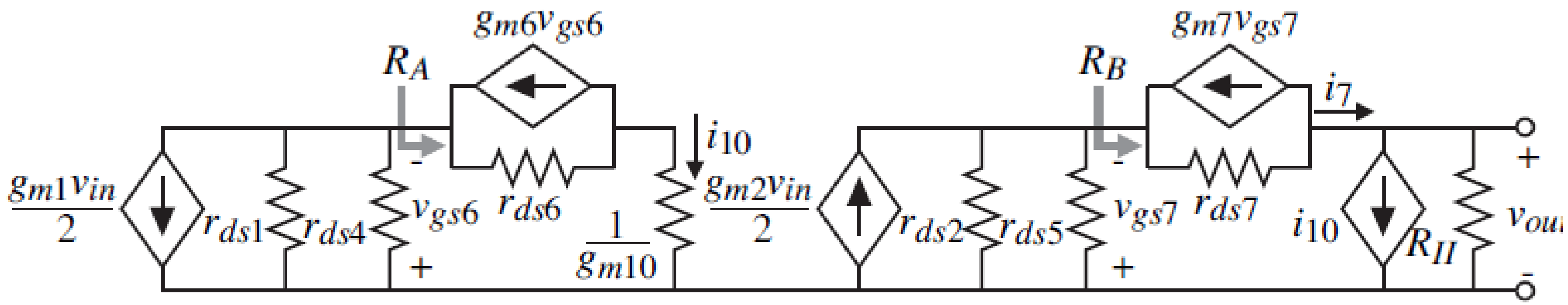




Equacionamento





Equacionamento

$$R_A = \frac{r_{ds6}+(1/g_{m10})}{1+g_{m6}r_{ds6}} \approx \frac{1}{g_{m6}}$$

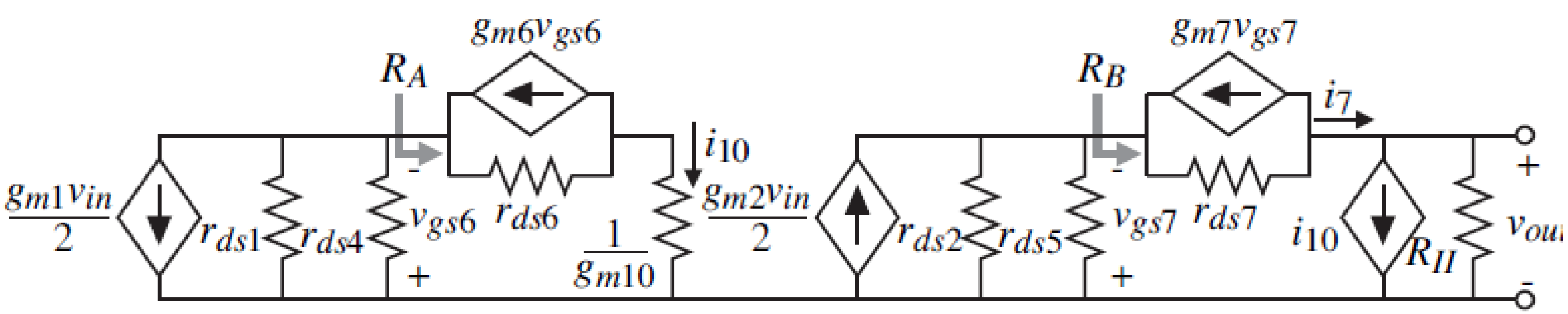
$$R_B = \frac{r_{ds7}+R_{II}}{1+g_{m7}r_{ds7}} \approx \frac{R_{II}}{g_{m7}r_{ds7}}$$

onde, $R_{II} \approx g_{m9}r_{ds9}r_{ds11}$

$$i_{10} = \frac{-g_{m1}(r_{ds1}||r_{ds4})v_{in}}{2[R_A+(r_{ds1}||r_{ds4})]} \approx \frac{-g_{m1}v_{in}}{2}$$

$$i_7 = \frac{g_{m2}(r_{ds2}||r_{ds5})v_{in}}{2\left[\frac{R_{II}}{g_{m7}r_{ds7}}+(r_{ds2}||r_{ds5})\right]} = \frac{g_{m2}v_{in}}{2\left(1+\frac{R_{II}(g_{ds2}+g_{ds5})}{g_{m7}r_{ds7}}\right)} = \frac{g_{m2}v_{in}}{2(1+k)}$$

where $k = \frac{R_{II}(g_{ds2}+g_{ds5})}{g_{m7}r_{ds7}}$



Equacionamento

$$R_A = \frac{r_{ds6}+(1/g_{m10})}{1 + g_{m6}r_{ds6}} \approx \frac{1}{g_{m6}}$$

$$R_B = \frac{r_{ds7} + R_{II}}{1 + g_{m7}r_{ds7}} \approx \frac{R_{II}}{g_{m7}r_{ds7}}$$

onde, $R_{II} \approx g_{m9}r_{ds9}r_{ds11}$

$$i_{10} = \frac{-g_{m1}(r_{ds1}||r_{ds4})v_{in}}{2[R_A + (r_{ds1}||r_{ds4})]} \approx \frac{-g_{m1}v_{in}}{2}$$

$$i_7 = \frac{g_{m2}(r_{ds2}||r_{ds5})v_{in}}{2\left[\frac{R_{II}}{g_{m7}r_{ds7}} + (r_{ds2}||r_{ds5})\right]} = \frac{g_{m2}v_{in}}{2\left(1 + \frac{R_{II}(g_{ds2}+g_{ds5})}{g_{m7}r_{ds7}}\right)} = \frac{g_{m2}v_{in}}{2(1+k)}$$

where $k = \dfrac{R_{II}(g_{ds2}+g_{ds5})}{g_{m7}r_{ds7}}$

$$\frac{v_{out}}{v_{in}} = \left(\frac{g_{m1}}{2} + \frac{g_{m2}}{2(1+k)}\right)R_{out} = \left(\frac{2+k}{2+2k}\right) g_{mI}R_{out}$$

$$R_{out} \approx (g_{m9}r_{ds9}r_{ds11})||[\,g_{m7}r_{ds7}(r_{ds2}||r_{ds5})]$$

$$\approx \left(\frac{g_m r_{ds}{}^2}{3}\right)$$

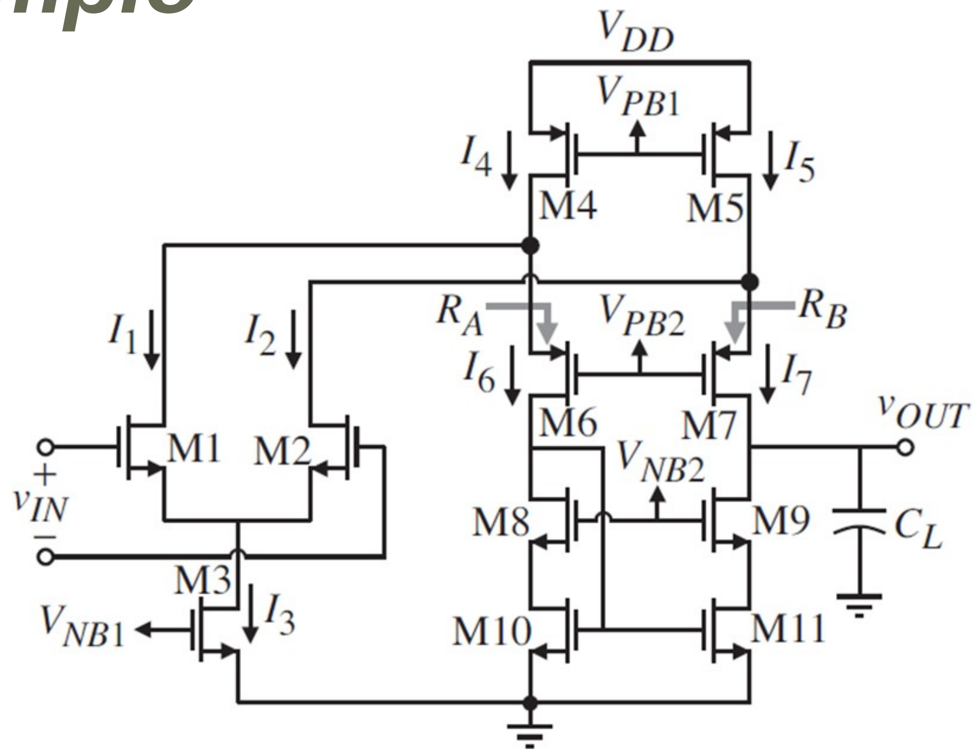
Etapas de projeto

Step	Relationship	Design Equation/Constraint	Comments
1	Slew Rate	$I_3 = SR \cdot C_L$	
2	Bias currents in output cascodes	$I_4 = I_5 = 1.2I_3$ to $1.5I_3$	Avoid zero current in cascodes
3	Maximum output voltage, v_{out}(max)	$S_5 = \frac{2I_5}{K_P' V_{SD5}^2}$, $S_7 = \frac{2I_7}{K_P' V_{SD7}^2}$, ($S_4 = S_5$ and $S_6 = S_7$)	$V_{SD5}(\text{sat}) = V_{SD7}(\text{sat}) = 0.5[V_{DD} - V_{out}(\text{max})]$
4	Minimum output voltage, v_{out}(min)	$S_{11} = \frac{2I_{11}}{K_N' V_{DS11}^2}$, $S_9 = \frac{2I_9}{K_N' V_{DS9}^2}$, ($S_{10} = S_{11}$ and $S_8 = S_9$)	$V_{DS9}(\text{sat}) = V_{DS11}(\text{sat}) = 0.5[V_{out}(\text{min}) - V_{SS}]$
5	$GB = \frac{g_{m1}}{C_L}$	$S_1 = S_2 = \frac{g_{m1}^2}{K_N' I_3} = \frac{GB^2 C_L^2}{K_N' I_3}$	
6	Minimum input CM	$S_3 = \frac{2I_3}{K_N'\left(V_{in}(\text{min}) - V_{SS} - \sqrt{(I_3/K_N' S_1)} - V_{T1}\right)^2}$	
7	Maximum input CM	$S_4 = S_5 = \frac{2I_4}{K_P'\left(V_{DD} - V_{in}(\text{max}) + V_{T1}\right)^2}$	S_4 and S_5 must meet or exceed value in step 3
8	Differential Voltage Gain	$\frac{v_{out}}{v_{in}} = \left(\frac{g_{m1}}{2} + \frac{g_{m2}}{2(1+k)}\right) R_{out} = \left(\frac{2+k}{2+2k}\right) g_{mI} R_{out}$	$k = \frac{R_{II}(g_{ds2} + g_{ds4})}{g_{m7} r_{ds7}}$
9	Power dissipation	$P_{diss} = (V_{DD} - V_{SS})(I_3 + I_{10} + I_{11})$	

Exemplo

- Projete o Amp. Op ao lado com as seguintes especificações:

VDD = 2.5V	Av ≥ 3000V/V
GB = 10MHz	ICMR = 1V a 2.5V
Slew rate = 10V/us com 10pF de carga	
Dissipação de Potência < 5mW	
0.5V < Output swing < 2V	



- Dados da tecnologia:

Vtn = 0.5V	λ_N = 0.06V^{-1}
Vtp = 0.5V	λ_P = 0.08V^{-1}
Kn = 120uA/V^2	
Kp = 25uA/V^2	

- Demais dados de projeto:

L = 0.5um

(1) Slew Rate

$$I_3 = SR{\cdot}C_L = 10\text{x}10^6{\cdot}10^{-11} = 100\mu\text{A}$$

(2) Correntes de polarização na saída

$$I_4 = I_5 = 125\mu\text{A}$$

(3) Tensão de saída máxima

$$S_4 = S_5 = \frac{2{\cdot}125\mu\text{A}}{25\mu\text{A/V}^2{\cdot}(0.25\text{V})^2} = \frac{2{\cdot}125{\cdot}16}{25} = 160$$

e, assumindo um valor de corrente para o pior caso (M1 em corte)

$$S_6 = S_7 = \frac{2{\cdot}125\mu\text{A}}{25\mu\text{A/V}^2(0.25\text{V})^2} = \frac{2{\cdot}125{\cdot}16}{25} = 160$$

(4) Tensão de saída mínima

$$S_8 = S_9 = S_{10} = S_{11} = \frac{2{\cdot}I_8}{K_N' V_{DS8}{}^2} = \frac{2{\cdot}125}{120{\cdot}(0.25)^2} = 33$$

(5) Cálculo de S1 e S2 a partir de GB

$$S_1 = S_2 = \frac{GB^2 \cdot C_L{}^2}{K_N' I_3} = \frac{(20\pi \mathrm{x} 10^6)^2 (10^{-11})^2}{120\mathrm{x}10^{-6} \cdot 100\mathrm{x}10^{-6}} = 32.9 \approx 33$$

(6) ICM mínimo

$$S_3 = \frac{2I_3}{K_N' \left(V_{in}(\mathrm{min}) - V_{SS} - \sqrt{\frac{I_3}{K_N' S_1}} - V_{T1} \right)^2} = \frac{200\mathrm{x}10^{-6}}{120\mathrm{x}10^{-6} \left(1.0 + 0 - \sqrt{\frac{100}{120 \cdot 33}} - 0.5 \right)^2} = 14.3 \approx 15$$

(7) ICM máximo

$$S_4 = S_5 \geq \frac{2I_4}{K_P' [V_{DD} - V_{in}(\mathrm{max}) + V_{T1}]^2} = \frac{2 \cdot 125\mu\mathrm{A}}{25\mathrm{x}10^{-6} \mu\mathrm{A/V}^2 [0.5\mathrm{V}]^2} = 40$$

(8) Cálculo do Ganho

$$S_4, S_5: \quad g_m = \sqrt{2\cdot125\cdot25\cdot160} = 1000\mu\text{S} \quad \text{and} \quad g_{ds} = 125\text{x}10^{-6}\cdot0.08 = 10\mu\text{S}$$

$$S_6, S_7: \quad g_m = \sqrt{2\cdot75\cdot25\cdot1600} = 774.6\mu\text{S} \quad \text{and} \quad g_{ds} = 75\text{x}10^{-6}\cdot0.08 = 6\mu\text{S}$$

$$S_8, S_9, S_{10}, S_{11}: \quad g_m = \sqrt{2\cdot75\cdot120\cdot20} = 600\mu\text{S} \quad \text{and} \quad g_{ds} = 75\text{x}10^{-6}\cdot0.06 = 4.5\mu\text{S}$$

$$S_1, S_2: \quad g_{mI} = \sqrt{2\cdot50\cdot120\cdot33} = 629\mu\text{S} \text{ and } g_{ds} = 50\text{x}10^{-6}(0.06) = 3\mu\text{S}$$

$$R_{II} \approx g_{m9}r_{ds9}r_{ds11} = (600\mu\text{S})\left(\frac{1}{4.5\mu\text{S}}\right)\left(\frac{1}{4.5\mu\text{S}}\right) = 38.25\ \text{M}\Omega$$

$$R_{out} \approx 29.63\text{M}\Omega || (774.6\mu\text{S})\left(\frac{1}{6\mu\text{S}}\right)\left(\frac{1}{10\mu\text{S}+3\mu\text{S}}\right) = 7.44\text{M}\Omega$$

$$k = \frac{R_{II}(g_{ds2}+g_{ds4})}{g_{m7}r_{ds7}} = \frac{38.25\text{M}\Omega(3\mu\text{S}+10\mu\text{S})(6\mu\text{S})}{774.6\mu\text{S}} = 3.85$$

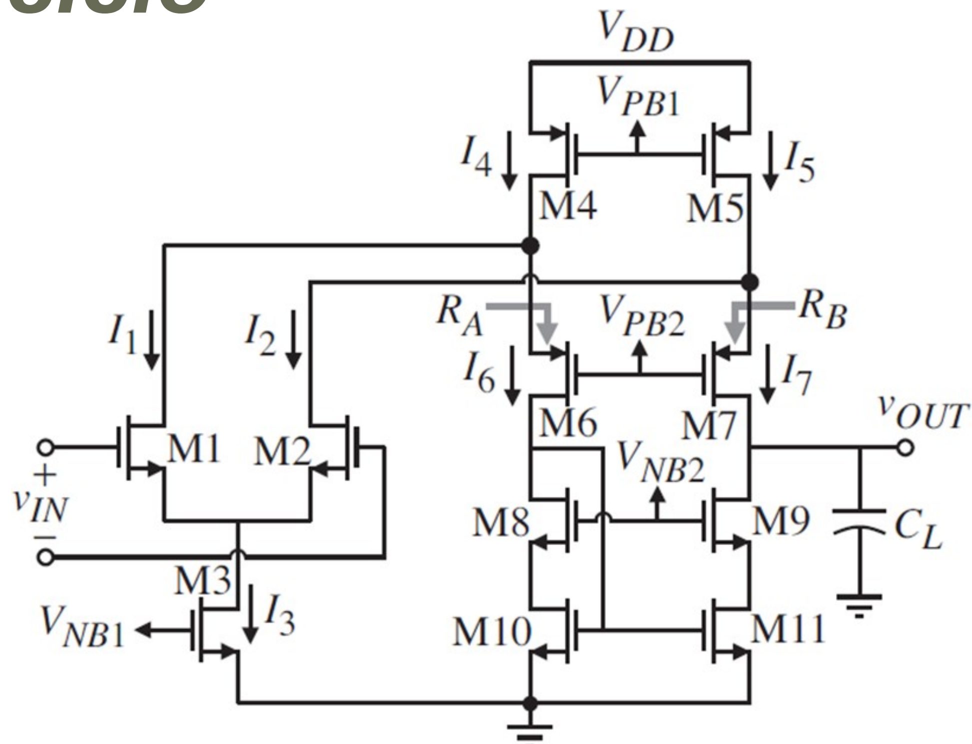
$$A_{vd} = \left(\frac{2+k}{2+2k}\right) g_{mI}R_{out} = 2987\ \text{V/V}$$

Próximo da especificação (3000V/V)

(9) Dissipação de potência

$$P_{diss} = 2.5\text{V}(100\text{uA}+125\text{uA}+125\text{uA}) = 0.875\text{mW}$$

Exercício



- Projete o Amp. Op ao lado com as seguintes especificações:

VDD = 1,8V	Av ≥ 5000V/V
GB = 5MHz	ICMR = 0,8V a 1,3V
Slew rate = 2V/us com 5pF de carga	
GB = 5MHz com 2pF de carga	
Dissipação de Potência < 5mW	
0,3V < Output swing < 0,8V	

- Dados da tecnologia:

Vtn = 0,397V	λ_N = 0,06V^{-1}
Vtp = 0,457V	λ_P = 0,08V^{-1}
Kn = 591uA/V^2	Cox = 8,82E-15 F/um2
Kp = 216uA/V^2	

- Demais dados de projeto:

Lmin e Wmin = 0,5um

Referências

- Phillip Allen, Douglas Holberg, " CMOS Analog Circuit Design", **Capítulo 6** Oxford, 2a ed., 2002.