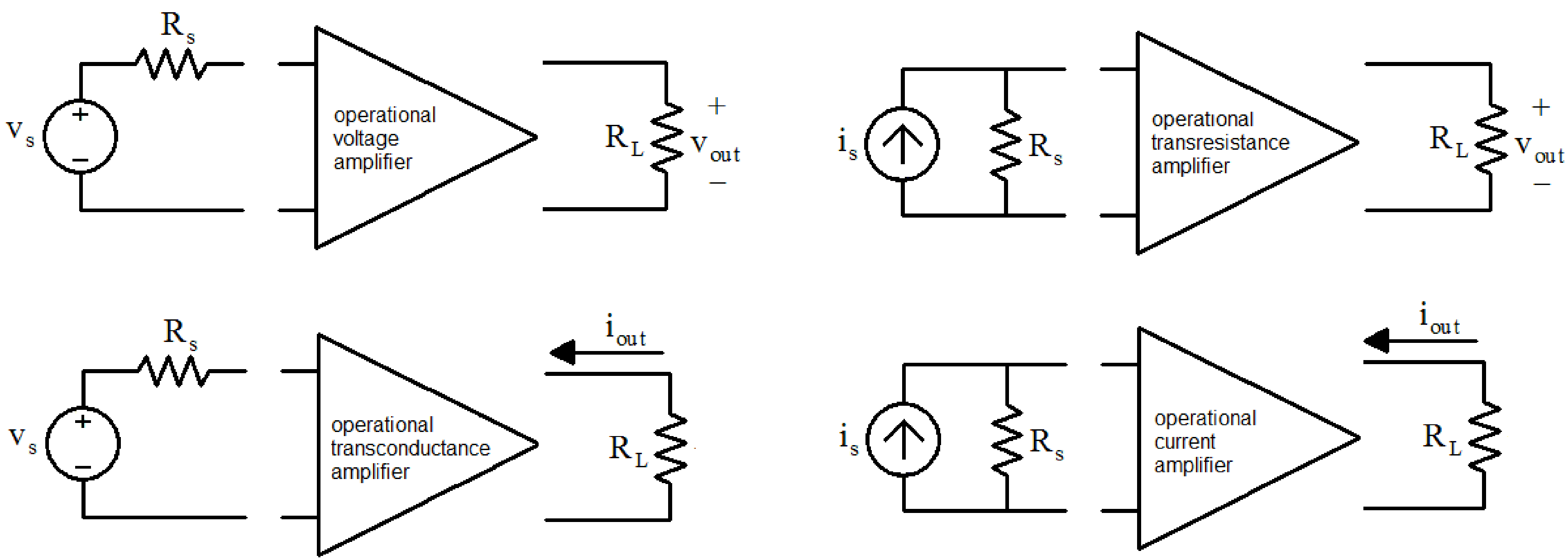
Операционни усилватели -1

Проектиране на аналогови интегрални схеми

Емил Д. Манолов, edm@tu-sofia.bg
кат. “Електронна техника”, Технически университет - София

Видове операционни усилватели



- стандартни операционни усилватели (operational voltage amplifier, Op Amp):
  вход – напрежение, изход – напрежение.
- операционни усилватели на проводимост (operational transconductance amplifier, OTA):
  вход – напрежение, изход – ток.
- операционни трансимпедансни усилватели (operational transresistance amplifier, OTRA):
  вход – ток, изход – напрежение.
- операционни усилватели на ток (operational current amplifier, OCA):
  вход – ток, изход – ток.

Операционни усилватели на проводимост

Намират приложение при обработка на аналогови и дискретни сигнали вътре в интегралните схеми (наличие само на капацитивен товар).

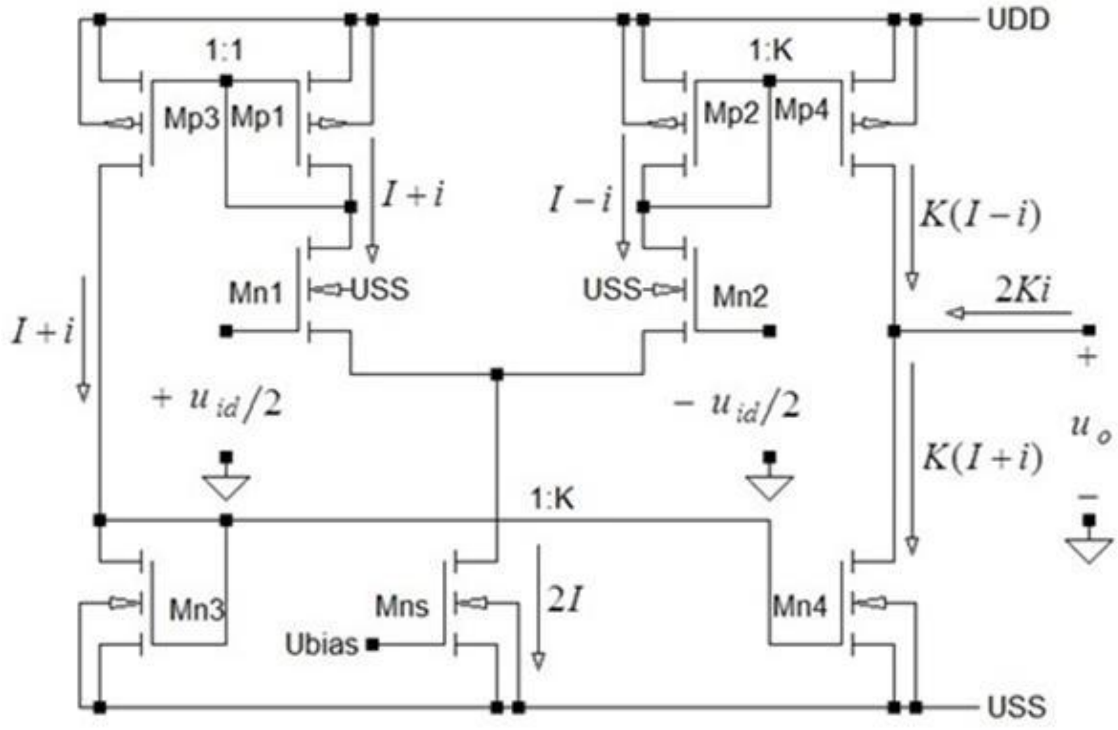
Характеристика на операционните усилватели на проводимост (ОТА):

- високо входно съпротивление r_{in};
- високо изходно съпротивление r_{out} (r_o);
- стръмност $G_m = i_{out}/u_{in}$;
- изходно напрежение $u_{out} = i_{out}\, r_{out} = G_m\, r_{out}\, u_{in}$.

Видове:

- ОТА с токови огледала;
- ОТА с прегънат каскод;
- ОТА на Милер.

OTA с прости токови огледала



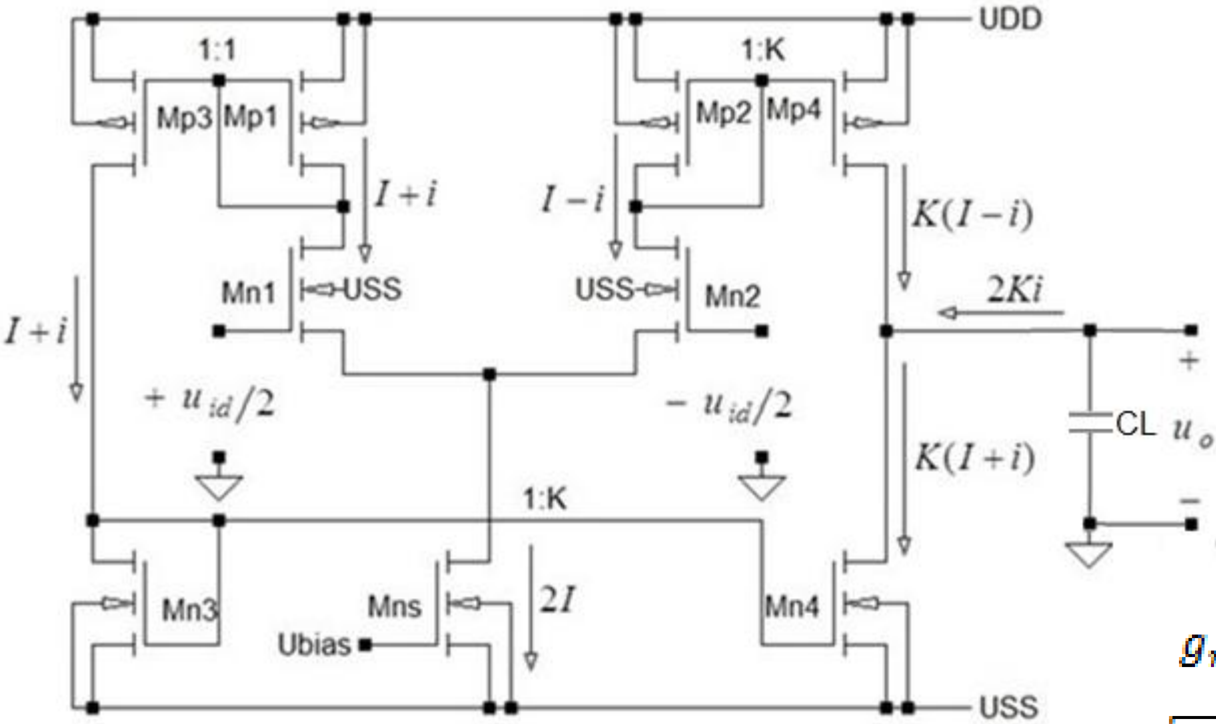
$$i_{out} = 2Ki = 2Kg_{mn1}\frac{u_{id}}{2} = Kg_{mn1}u_{id}$$

$$r_{out} = \frac{1}{g_{dsn4} + g_{dsp4}}$$

$$u_{out} = -i_{out}r_{out} = -\frac{Kg_{mn1}u_{id}}{g_{dsn4} + g_{dsp4}}$$

$$A_{ud} = \frac{u_{out}}{u_{id}} = -\frac{Kg_{mn1}}{g_{dsn4} + g_{dsp4}}$$

АЧХ на ОТА с просто токово огледало



$$BW=\frac{1}{2\pi r_{out}C_L}$$

$$r_{out}=\frac{1}{g_{dsn4}+g_{dsp4}}$$

$$BW=\frac{g_{dsn4}+g_{dsp4}}{2\pi C_L}$$

$$BW=\frac{(\lambda_n+\lambda_p)KI}{2\pi C_L}$$

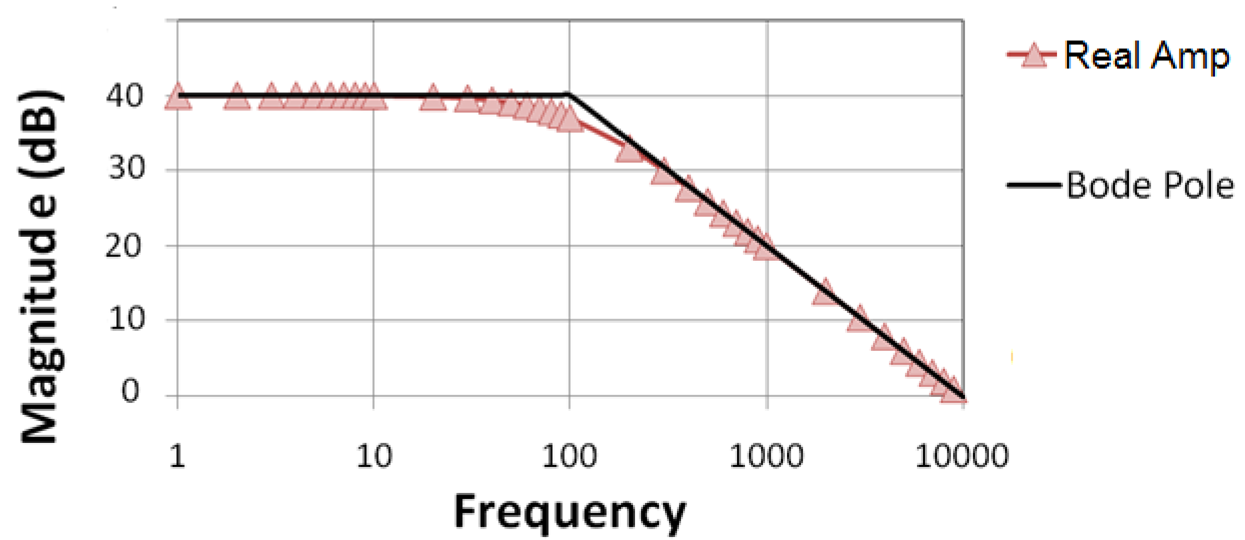
$$g_{mn1}=\sqrt{2\mu_n C_{ox}{}^{W1}/_{L1}\,I}=\frac{2I}{U_{eff}}$$

$$A_{ud}=\frac{Kg_{mn1}}{g_{dsn4}+g_{dsp4}}=\frac{Kg_{mn1}}{(\lambda_n+\lambda_p)KI}=\frac{g_{mn1}}{(\lambda_n+\lambda_p)I}=\frac{\sqrt{2\mu_n C_{ox}{}^{W1}/_{L1}}}{(\lambda_n+\lambda_p)\sqrt{I}}=\frac{2}{(\lambda_n+\lambda_p)U_{eff}}$$

$$GBW=A_{ud}BW=\frac{Kg_{mn1}}{2\pi C_L}=\frac{K\sqrt{2\mu_n C_{ox}{}^{W1}/_{L1}}}{2\pi C_L}=\frac{KI}{\pi U_{eff}C_L}$$

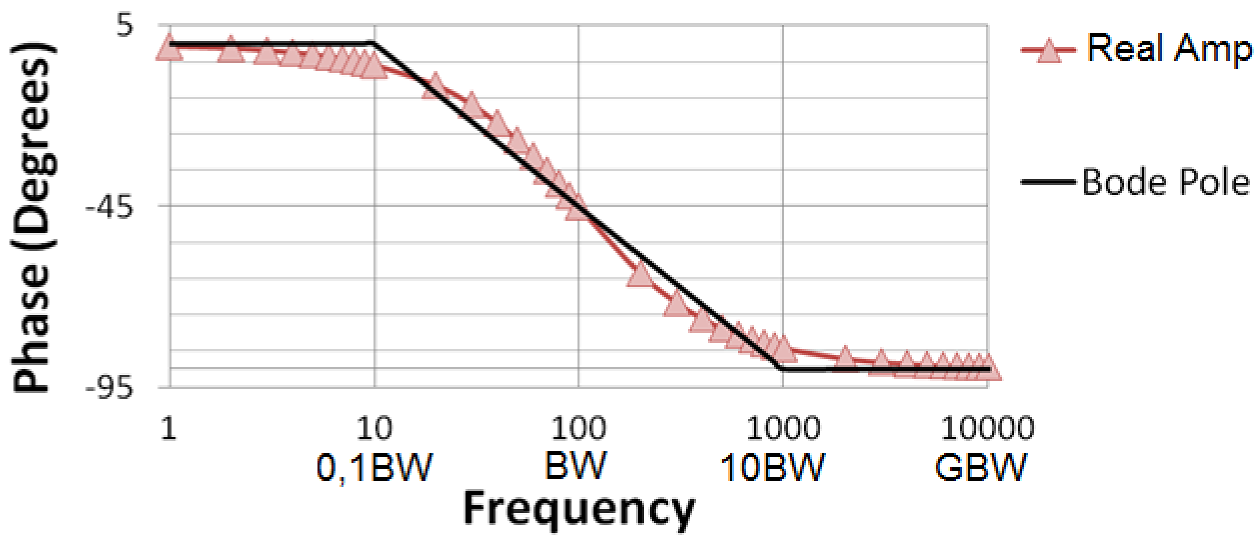
$$SR=\frac{2KI}{C_L}$$

Диаграми на Боде

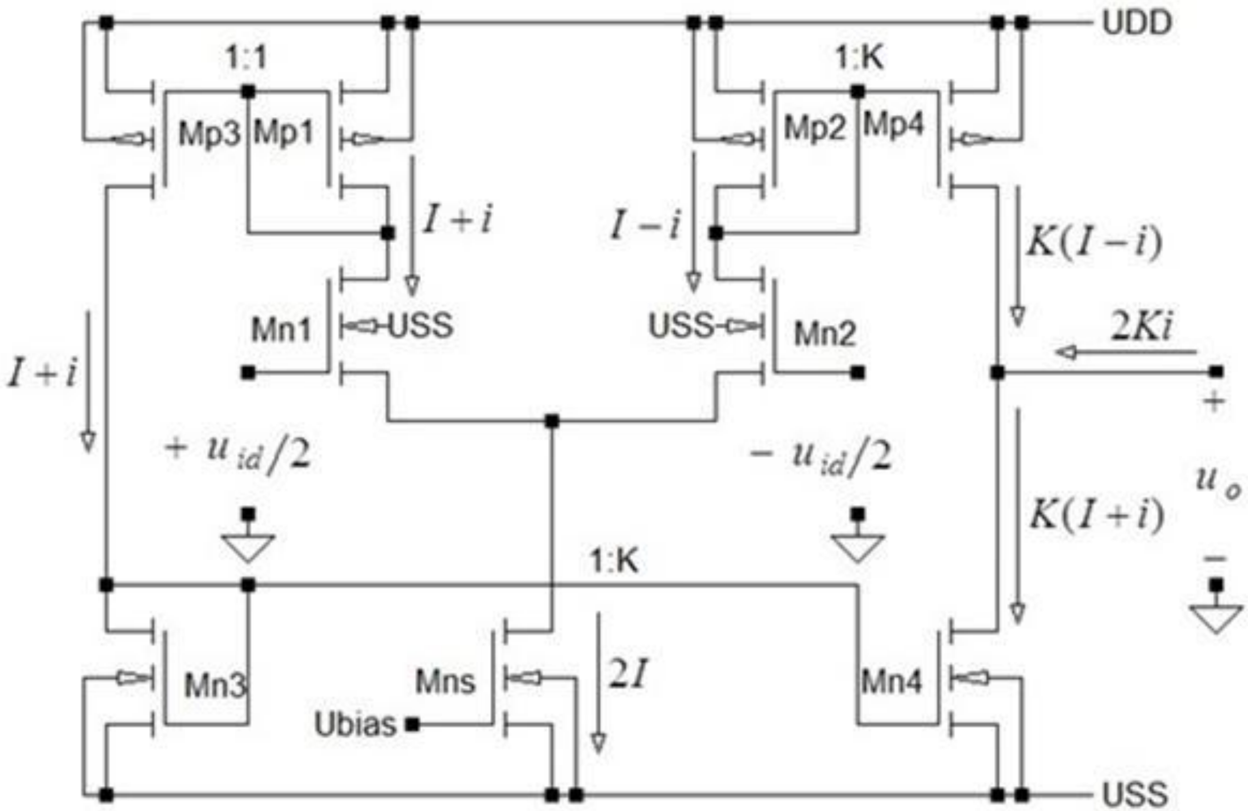


$$\text{Phase} = -\text{arctg}\frac{f}{f_\beta}$$

$$f_\beta = f_{(-3dB)} = BW$$



Проектиране на ОТА с прости токови огледала



Дадено: GBW=10 MHz ;
CL=10pF

Да се определят: I, $\frac{W}{L}$,
Aud, BW, SR

Решение:

$$GBW = |A_{ud}|BW = \frac{Kg_{mn1}}{2\pi C_L}$$

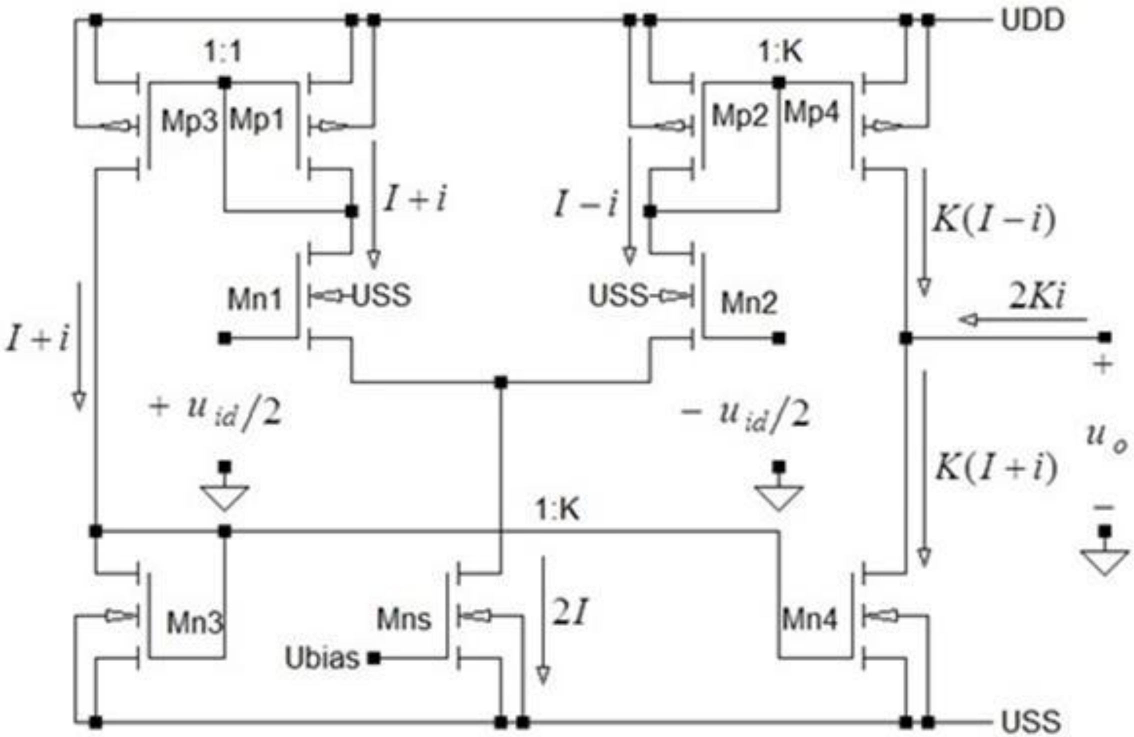
$$Kg_{mn1} = 2\pi C_L \cdot GBW$$

$$Kg_{mn1} = 2\pi \cdot 10pF \cdot 10MHz \approx 628\frac{\mu A}{V}; \quad Kg_{mn1} \approx 628\frac{\mu A}{V} = K\frac{2I}{U_{eff}};$$

Избираме: K=4; Ueff=0,2V ; $I = \frac{Kg_{mn1}}{2K}Ueff = \frac{628}{2 \cdot 4}0.2 = 15{,}7\mu A;$

Приемаме:
$\boldsymbol{I = 18\,\mu A}$

Проектиране на ОТА с прости токови огледала



Оразмеряване на схемата:

$$I_{Dn} = \frac{K_n}{2}\frac{W}{L}U_{eff}^2\,; \qquad \frac{W}{L} = \frac{2I_{Dn}}{K_n U_{eff}^2}$$

$I_{Dn1} = I_{Dn2} = I_{Dn3} = I = 18\mu A$

Wn1/Ln1=Wn2/Ln2=Wn3/Ln3=18/2

$I_{Dns} = 2I = 36\mu A$

Wns/Lns=36/2

$I_{Dn4} = 4I = 72\mu A$

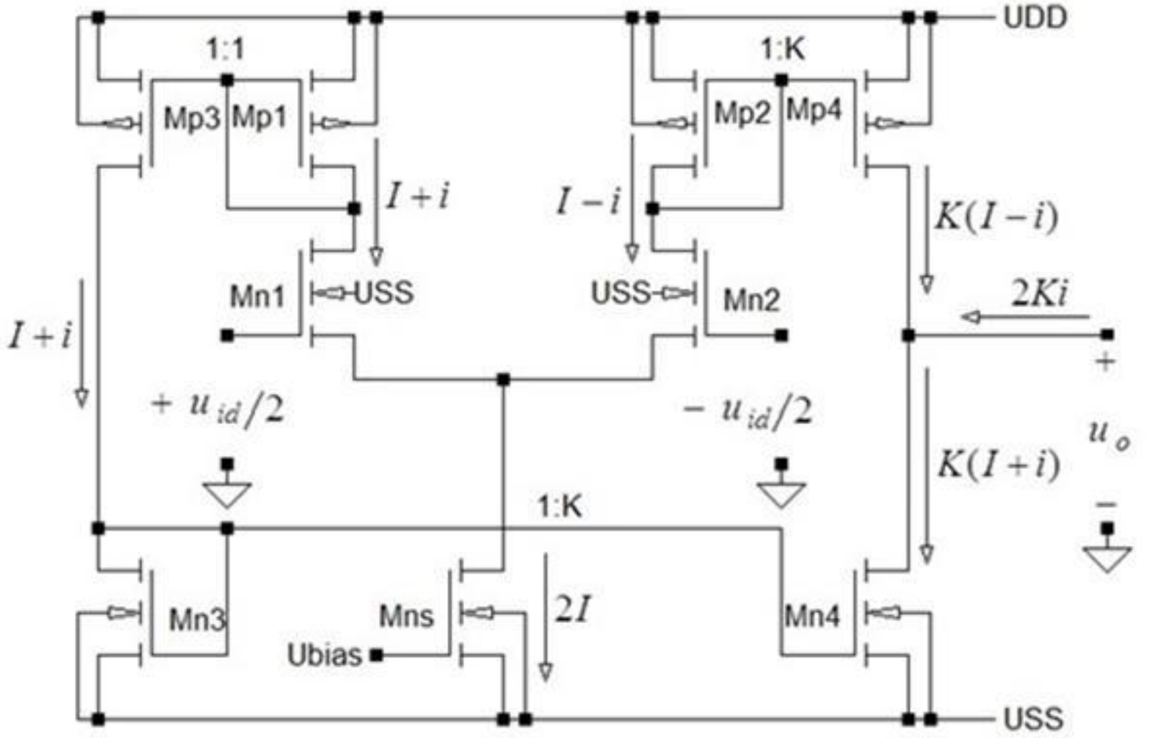
Wn4/Ln4=72/2

$$I_{Dp} = \frac{K_p}{2}\frac{W}{L}U_{eff}^2\,; \qquad \frac{W}{L} = \frac{2I_{Dp}}{K_p U_{eff}^2}\,;$$

$I_{Dp1} = I_{Dp2} = I_{Dp3} = I = 18\mu A\,;$ Wp1/Lp1=Wp2/Lp2=Wp3/Lp3=45/2

$I_{Dp4} = 4I = 72\mu A;$ Wp4/Lp4=180/2

Проектиране на ОТА с прости токови огледала



$$BW = \frac{(\lambda_n + \lambda_p)KI}{2\pi C_L}$$

$BW = 36{,}6\ kHz;$

$$GBW = A_{ud} BW$$

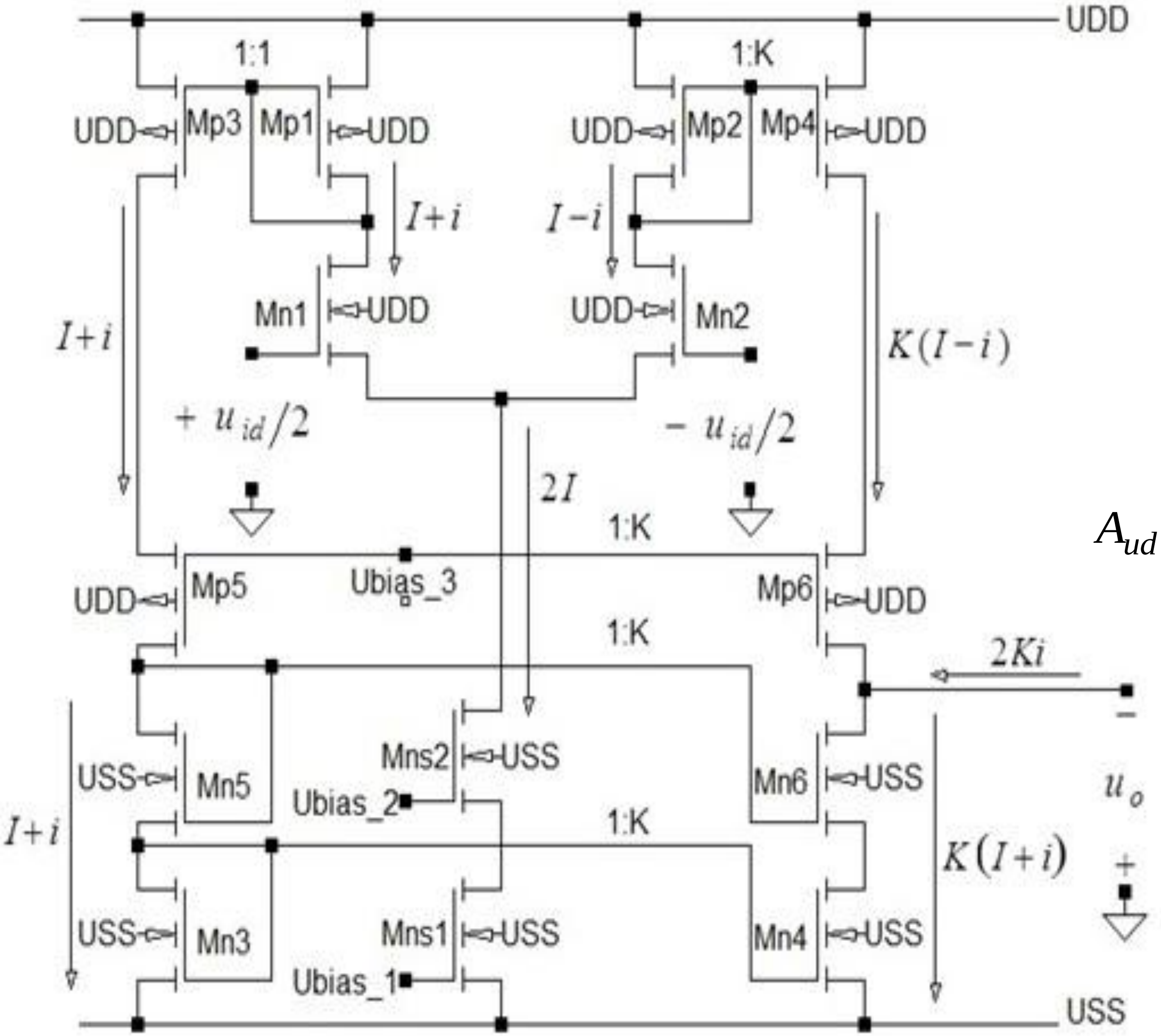
$GBW = 11{,}6\ MHz;$

$$SR = \frac{2KI}{C_L}$$

$SR = 14{,}4\ V/\mu s$

$$A_{ud} = -\frac{K g_{mn1}}{g_{dsn4} + g_{dsp4}} = -\frac{K g_{mn1}}{(\lambda_{n4} + \lambda_{p4})KI} = -\frac{g_{mn1}}{(\lambda_{n4} + \lambda_{p4})I}$$
$$= -\frac{2I/U_{eff}}{(\lambda_{n4} + \lambda_{p4})I} = -\frac{2}{(\lambda_{n4} + \lambda_{p4})U_{eff}} = -312{,}5$$

OTA с каскодни токови огледала

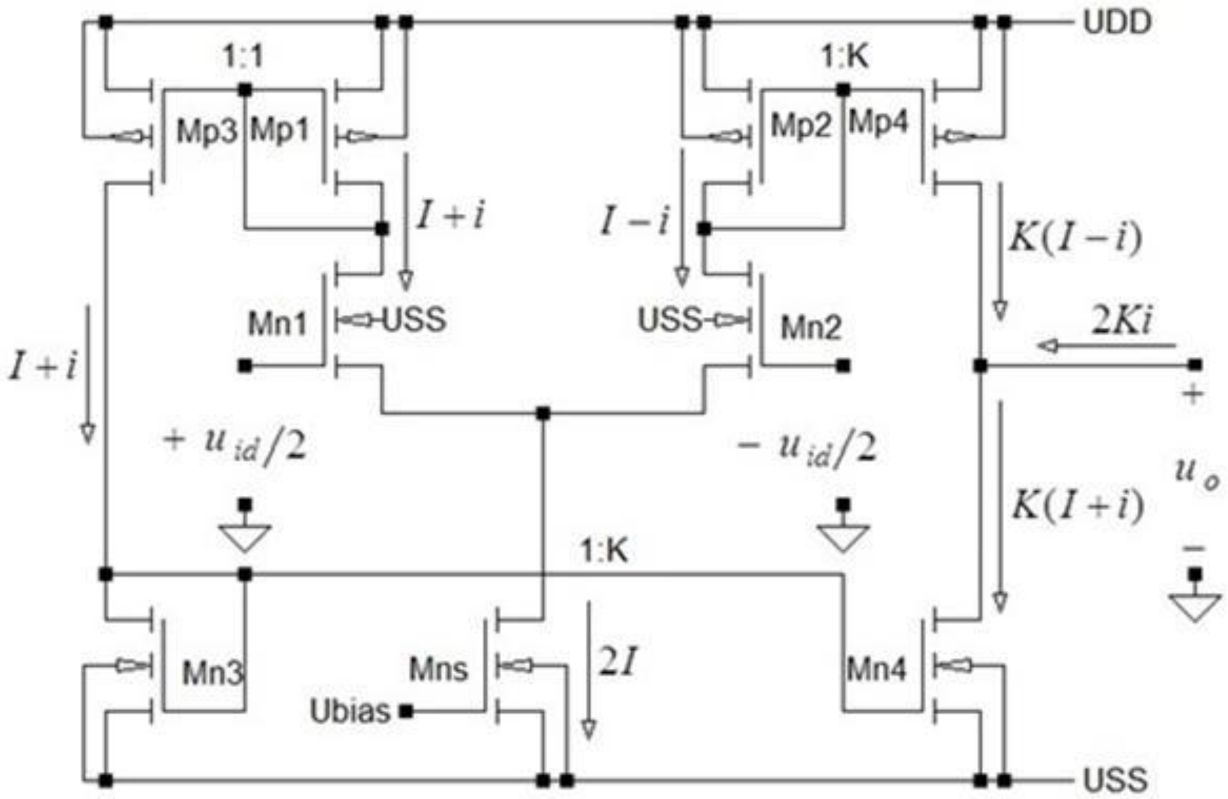


$$g_{dsn6-4} = \frac{g_{dsn6}\, g_{dsn4}}{g_{mn6}}$$

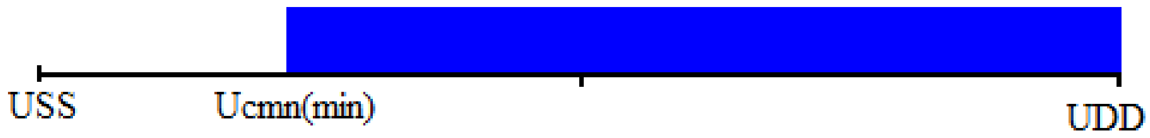
$$g_{dsp6-4} = \frac{g_{dsp6}\, g_{dsp4}}{g_{mp6}}$$

$$A_{ud} = \frac{u_{out}}{u_{id}} = -\frac{K g_{mn1}}{g_{dsp6-4} + g_{dsn6-4}}$$

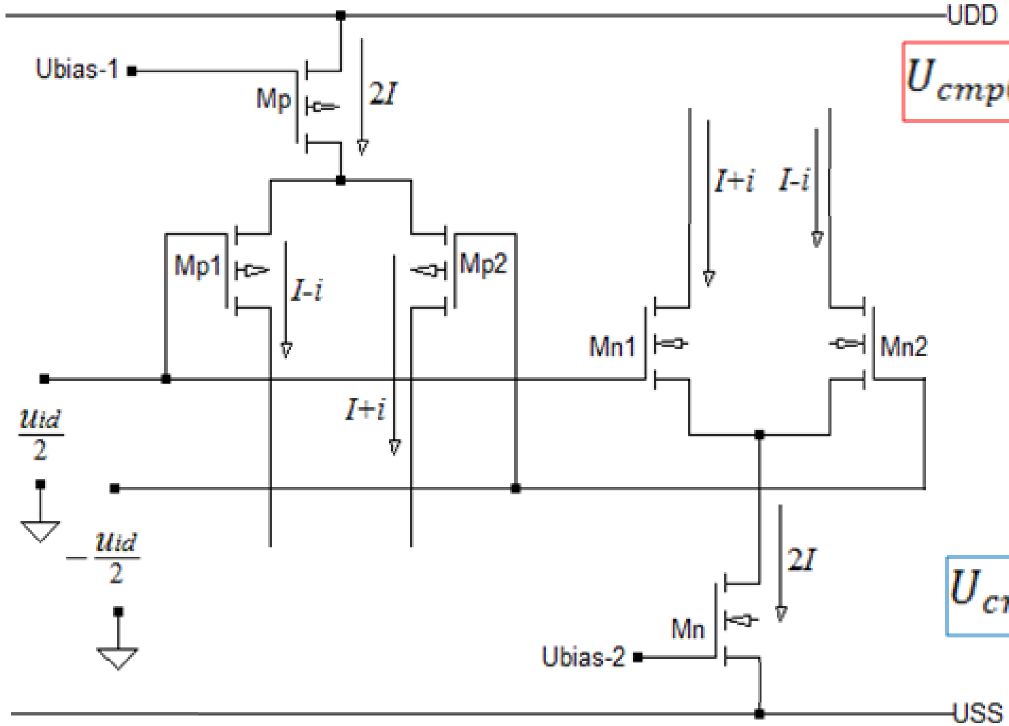
Определяне на размаха на входния синфазен сигнал



$$U_{cmn(min)} = U_{ss} + U_{DSns} + U_{GSn(min)}$$

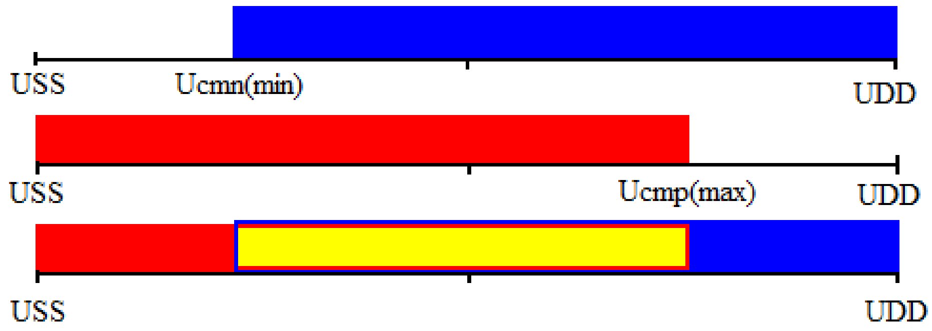


Повишаване на размаха на входния сигнал

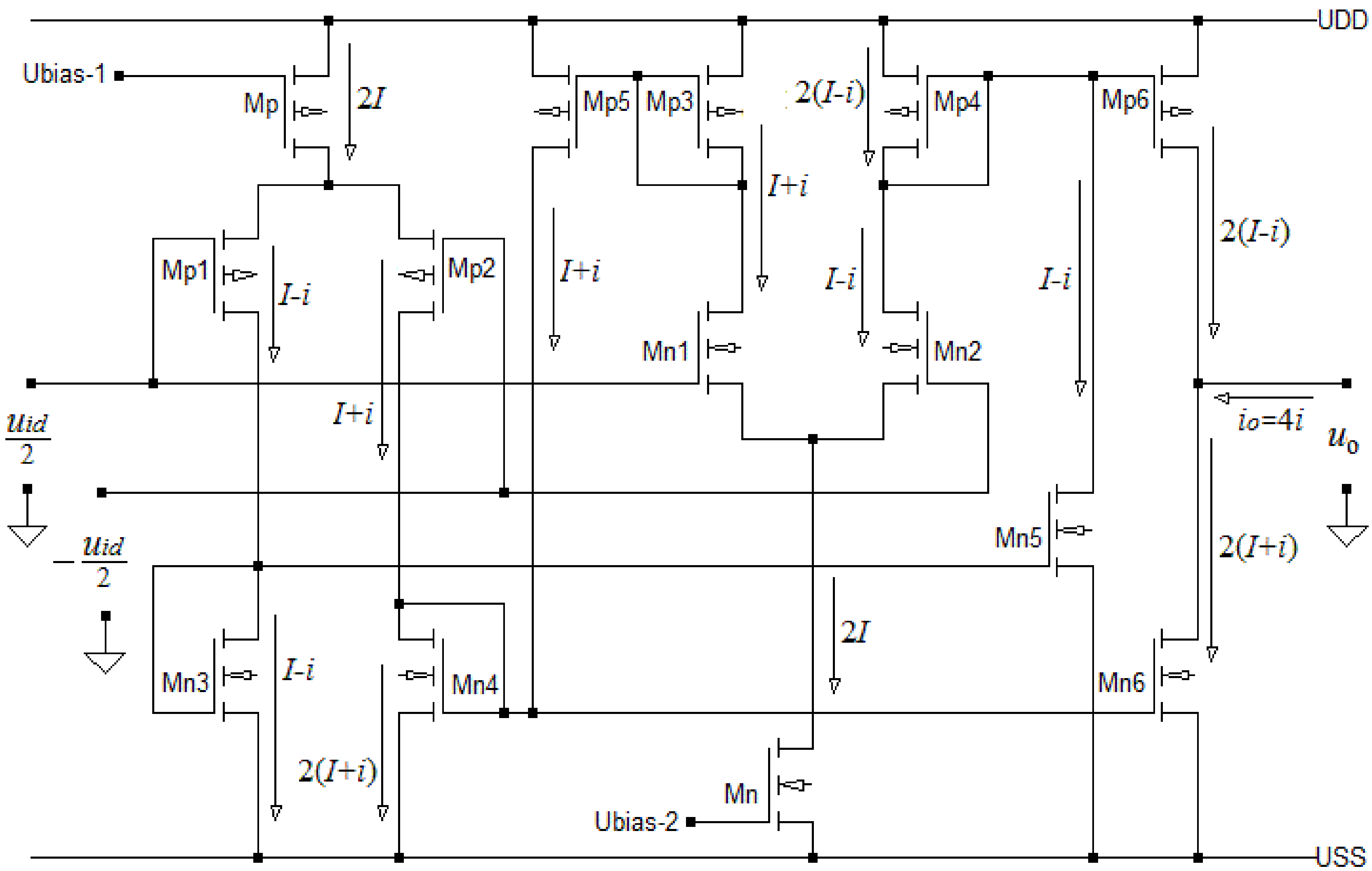


$$U_{cmp(max)} = U_{DD} - |U_{DSp}| - |U_{GSp1(min)}|$$

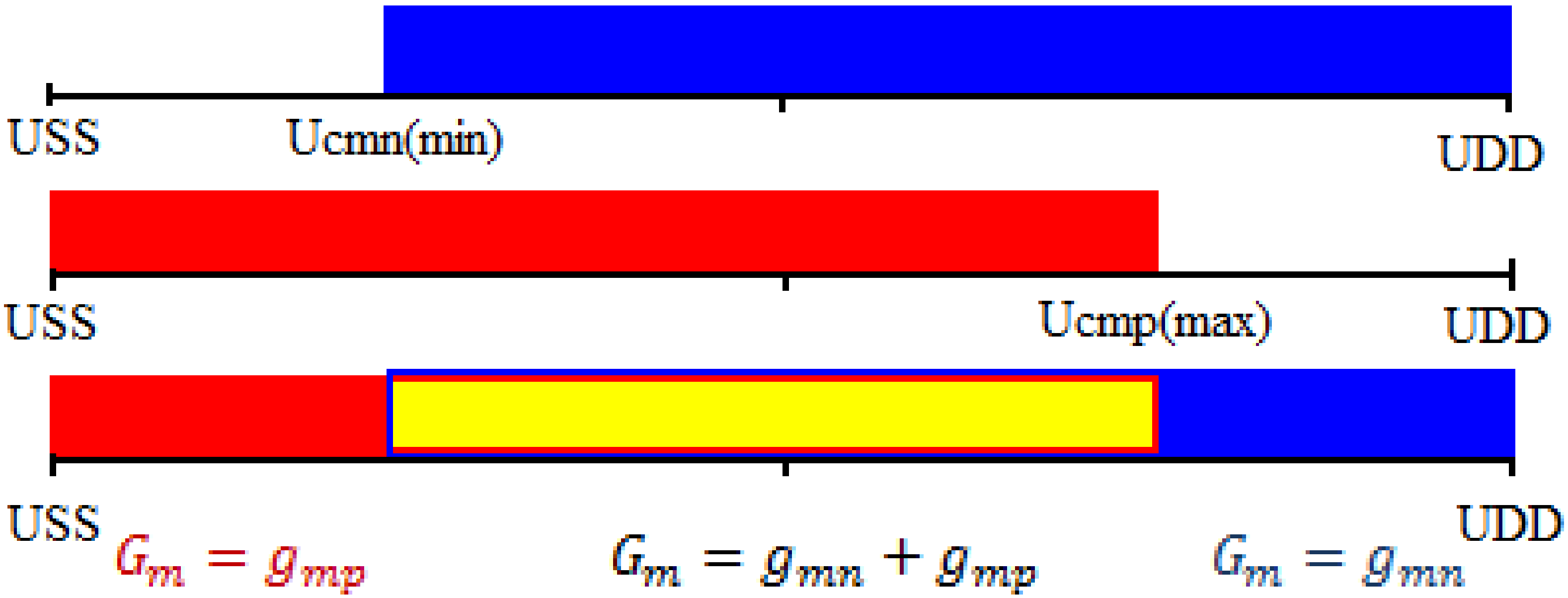
$$U_{cmn(min)} = U_{ss} + U_{DSn} + U_{GSn1(min)}$$



ОТА с повишен размах на входния сигнал



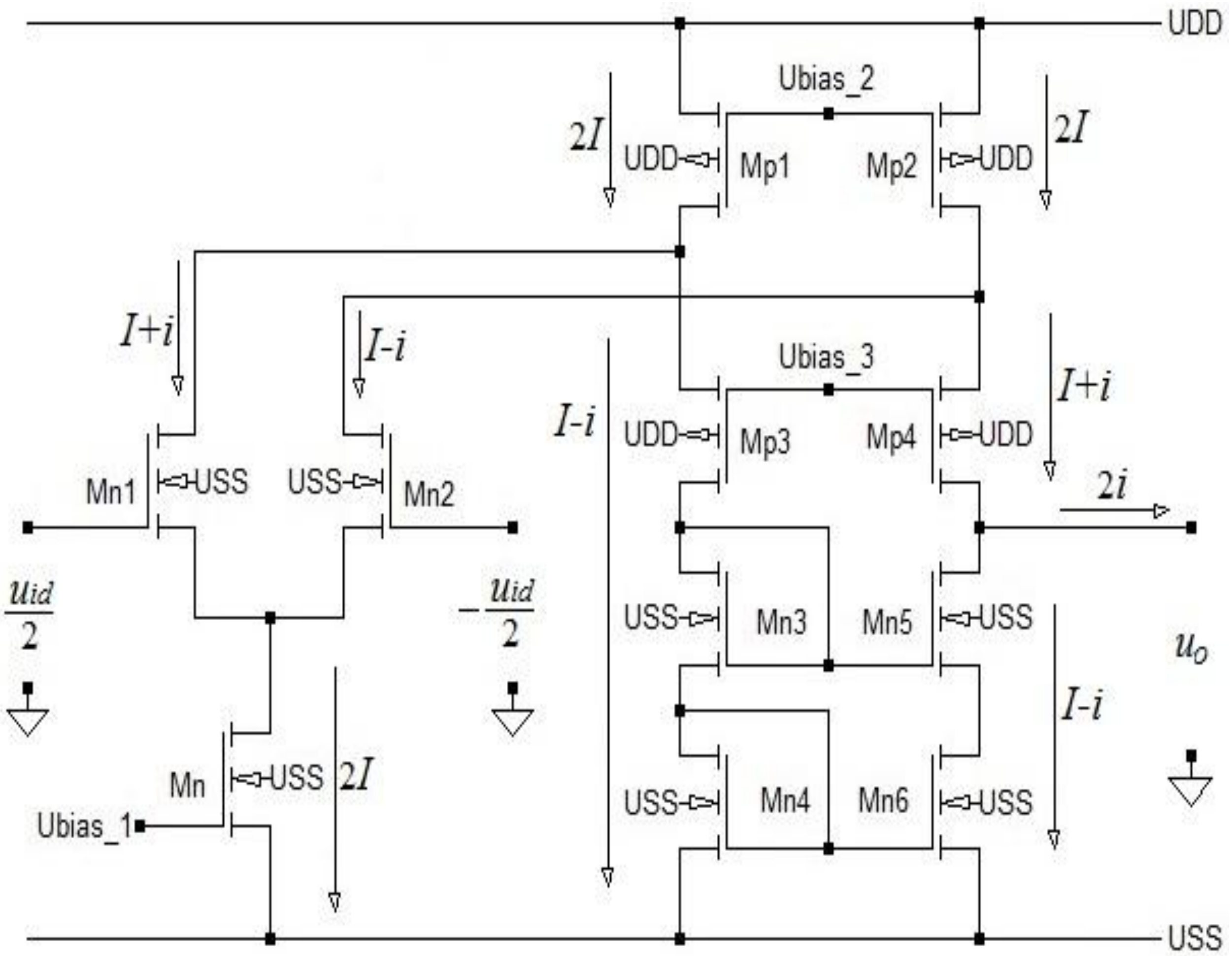
ОТА с повишен размах на входния сигнал



$$U_{SS} \le U_{cm} \le U_{cmn(min)} \;\rightarrow\; G_m = g_{mp}; \qquad U_{cmp(max)} < U_{cm} < U_{DD} \;\rightarrow\; G_m = g_{mn};$$

$$U_{cmn(min)} < U_{cm} < U_{cmp(min)} \;\rightarrow\; G_m = g_{mn} + g_{mp}$$

ОТА с прегънат каскод



$$r_o = \frac{1}{g_{dsn5-6} + g_{dsp4-2}}$$

$$g_{dsn5-6} = \frac{g_{dsn5} g_{dsn6}}{g_{mn5}}$$

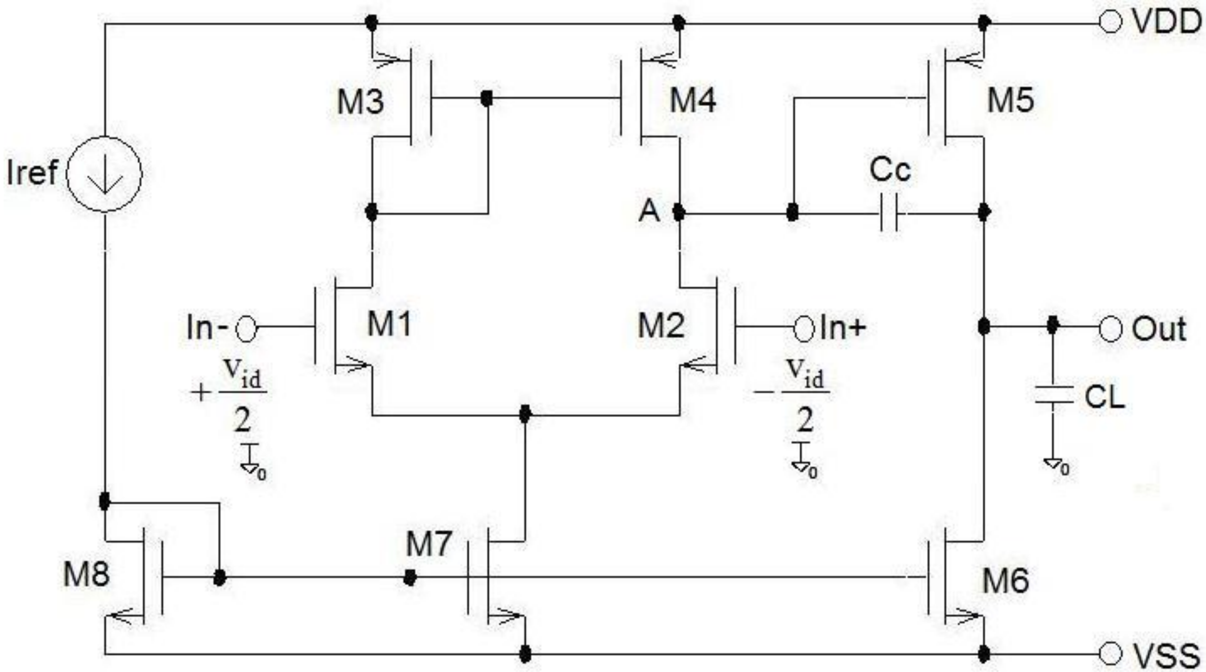
$$g_{dsp4-2} = \frac{g_{dsp4} g_{ds2}}{g_{mp4}}$$

$$g_{ds2} = g_{dsn2} + g_{dsp2}$$

$$A_u = \frac{u_o}{u_{id}} = \frac{i_o r_o}{u_{id}}$$

$$A_u = \frac{g_{mn1}}{g_{dsn5-6} + g_{dsp4-2}}$$

ОТА на Милер – АС анализ



$$i_{out} = g_{mp5} u_{Ad}$$

$$u_{Ad} = \frac{g_{mn2}}{g_{dsn2} + g_{dsp4}} u_{id}$$

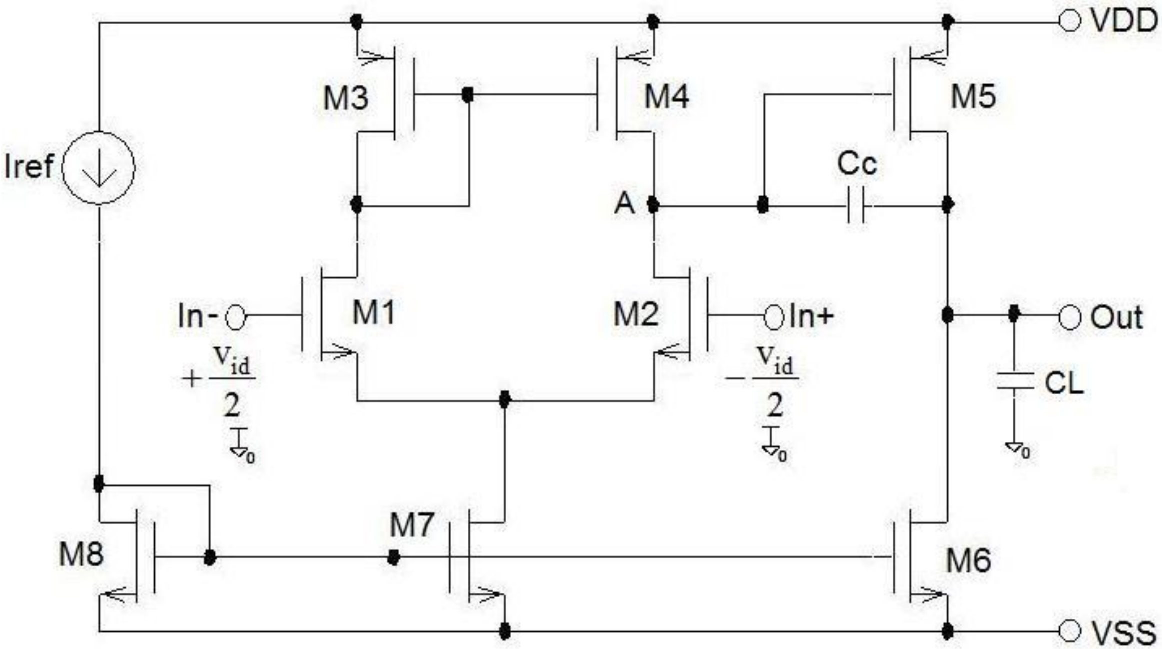
$$i_{out} = \frac{g_{mn2} g_{mp5}}{g_{dsn2} + g_{dsp4}} u_{id}$$

$$G_m = \frac{i_{out}}{u_{id}} = \frac{g_{mn2} \cdot g_{mp5}}{g_{dsn2} + g_{dsp4}}$$

$$r_{out} = \frac{1}{g_{dsp5} + g_{dsn6}}$$

$$A_u = G_m r_{out} = \frac{g_{mp5} \cdot g_{mn2}}{(g_{dsp5} + g_{dsn6}) \cdot (g_{dsn2} + g_{dsp4})}$$

ОТА на Милер – обобщение за Au



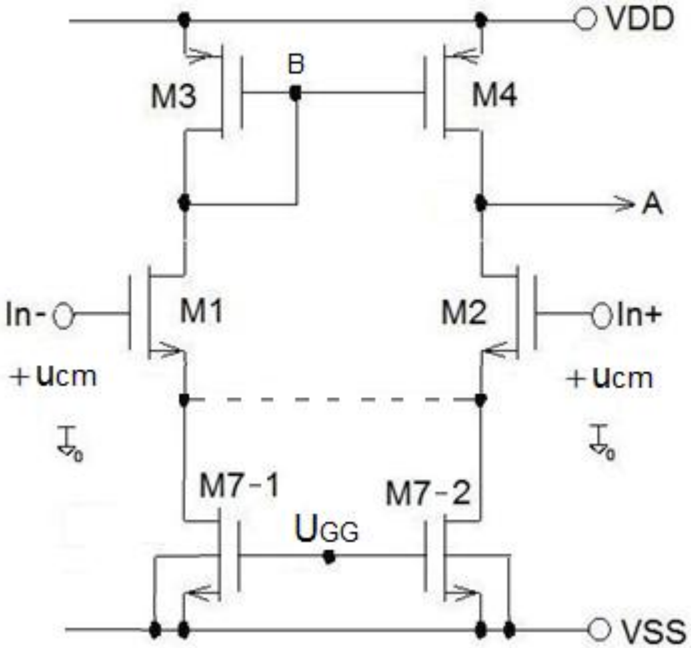
$$A_{ud1} = -\frac{g_{mn2}}{g_{dsn2} + g_{dsp4}}$$

$$A_{ud2} = -\frac{g_{mp5}}{g_{dsp5} + g_{dsn6}}$$

$$A_u = A_{u1}A_{u2} = \frac{g_{mn2}}{g_{dsn2} + g_{dsp4}} \frac{g_{mp5}}{g_{dsn6} + g_{dsp5}} = \frac{\sqrt{2K_n \frac{W2}{L2} I_{D2}}}{(\lambda_{n2} + \lambda_{p4})I_{D2}} \frac{\sqrt{2K_p \frac{W5}{L5} I_{D5}}}{(\lambda_{n6} + \lambda_{p5})I_{D5}} =$$

$$= \frac{2I_{D2}/U_{eff}}{(\lambda_{n2} + \lambda_{p4})I_{D2}} \frac{2I_{D5}/U_{eff}}{(\lambda_{n6} + \lambda_{p5})I_{D5}} \approx \frac{4}{(\lambda_n + \lambda_p)^2 U_{eff}^2}$$

ОТА на Милер –A_{ucm}



$$u_A = A_{ucm1}u_{cm} + A_{ucm2}u_B$$

$$u_B = A_{ucm3}u_{cm}$$

$$A_{ucm1} = -\frac{r_{ds4}}{r_{ds(7-2)}} = -\frac{g_{ds(7-2)}}{g_{ds4}} = -\frac{\lambda_n}{\lambda_p}$$

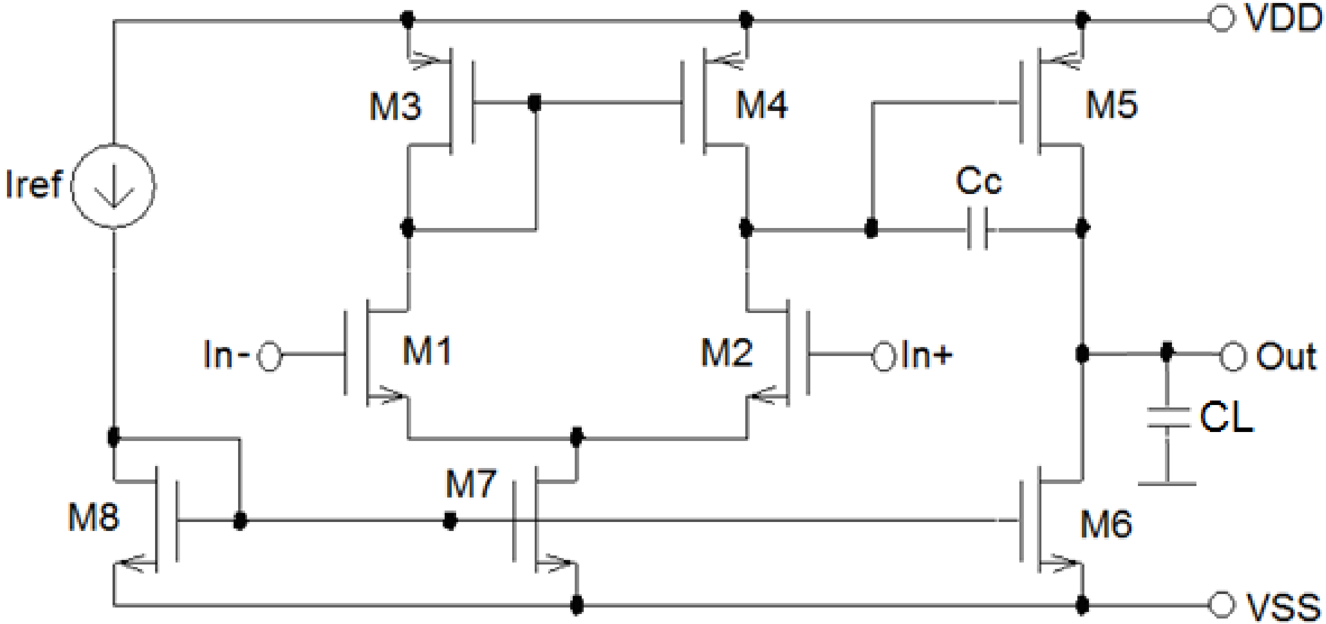
$$A_{ucm2} = -\frac{g_{m4}}{g_{ds4} + r_{ds2-(7-2)}} \approx -\frac{g_{m4}}{g_{ds4}} = -\frac{g_{m4}}{\lambda_p I}$$

$$A_{ucm3} = -\frac{r_{ds3}}{r_{ds(7-1)}} = -\frac{g_{ds(7-1)}}{g_{m3}} = -\frac{g_{ds(7-2)}}{g_{m4}} = -\frac{\lambda_n I}{g_{m4}}$$

$$u_A = A_{ucm1}u_{cm} + A_{ucm2}u_B = A_{ucm1}u_{cm} + A_{ucm2}A_{ucm3}u_{cm}$$

$$u_A = -\frac{\lambda_n}{\lambda_p}u_{cm} + \left(-\frac{g_{m4}}{\lambda_p I}\right)\left(-\frac{\lambda_n I}{g_{m4}}\right)u_{cm} = -\frac{\lambda_n}{\lambda_p}u_{cm} + \frac{\lambda_n}{\lambda_p}u_{cm} \approx 0$$

OTA на Милер – постояннотокови зависимости



Всички транзистори работят в областта на насищане.

$$I_{ref} = I_{D8} = \frac{\mu_n C_{ox}}{2} \frac{W8}{L8} V_{eff8}; \quad I_{D7} = \frac{W7/L7}{W8/L8} I_{D8} = \frac{W7/L7}{W8/L8} I_{ref}; \quad I_{D1} = I_{D2} = I_{D3} = I_{D4} = \frac{I_{D7}}{2};$$

Условие за постояннотоков баланс:

$$|V_{DS3}| = |V_{GS4}| = |V_{GS5}| \quad \Rightarrow \quad I_{D5} = I_{D4} \frac{W5/L5}{W4/L4} = I_{D3} \frac{W5/L5}{W3/L3}; \quad I_{D6} = I_{D7} \frac{W6/L6}{W7/L7} = 2I_{D4} \frac{W6/L6}{W7/L7};$$

$$I_{D5} = I_{D6} \Rightarrow \quad I_{D4} \frac{W5/L5}{W4/L4} = 2I_{D4} \frac{W6/L6}{W7/L7} \quad \Rightarrow \quad \frac{W5/L5}{W4/L4} = 2 \frac{W6/L6}{W7/L7}$$

Б л а г о д а р я !