Операционни усилватели - 2

Проектиране на аналогови интегрални схеми

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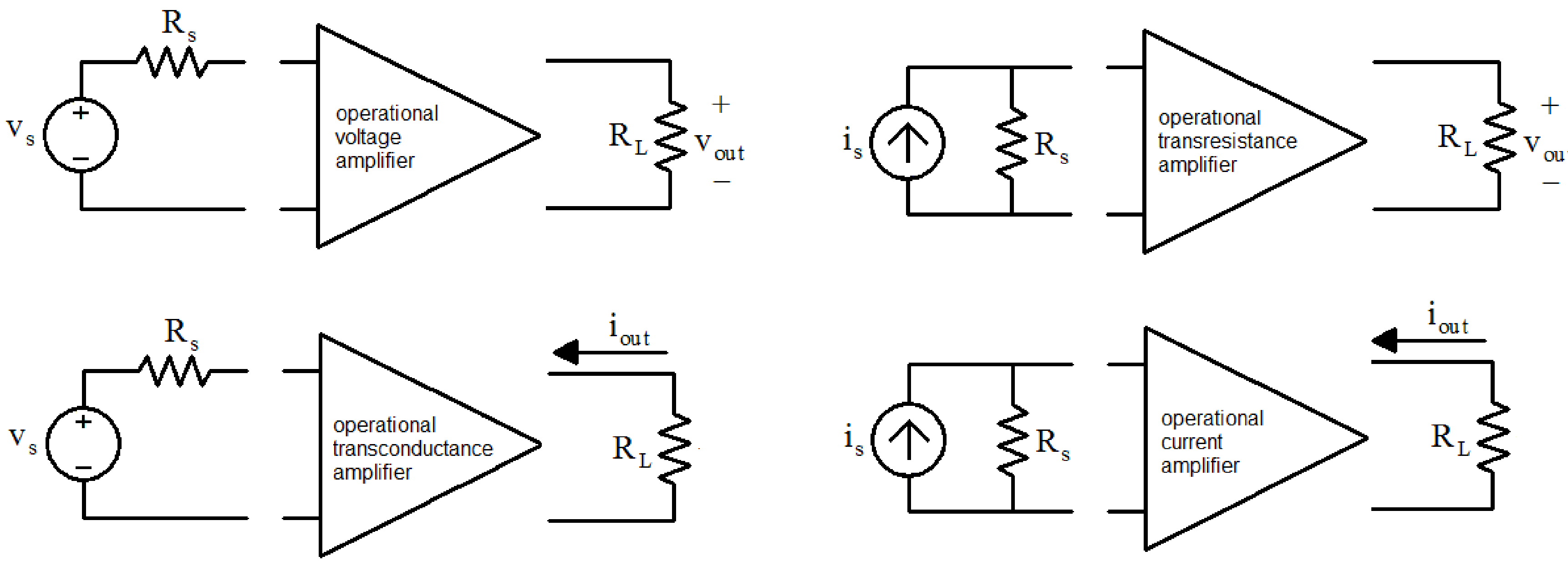
Видове операционни усилватели

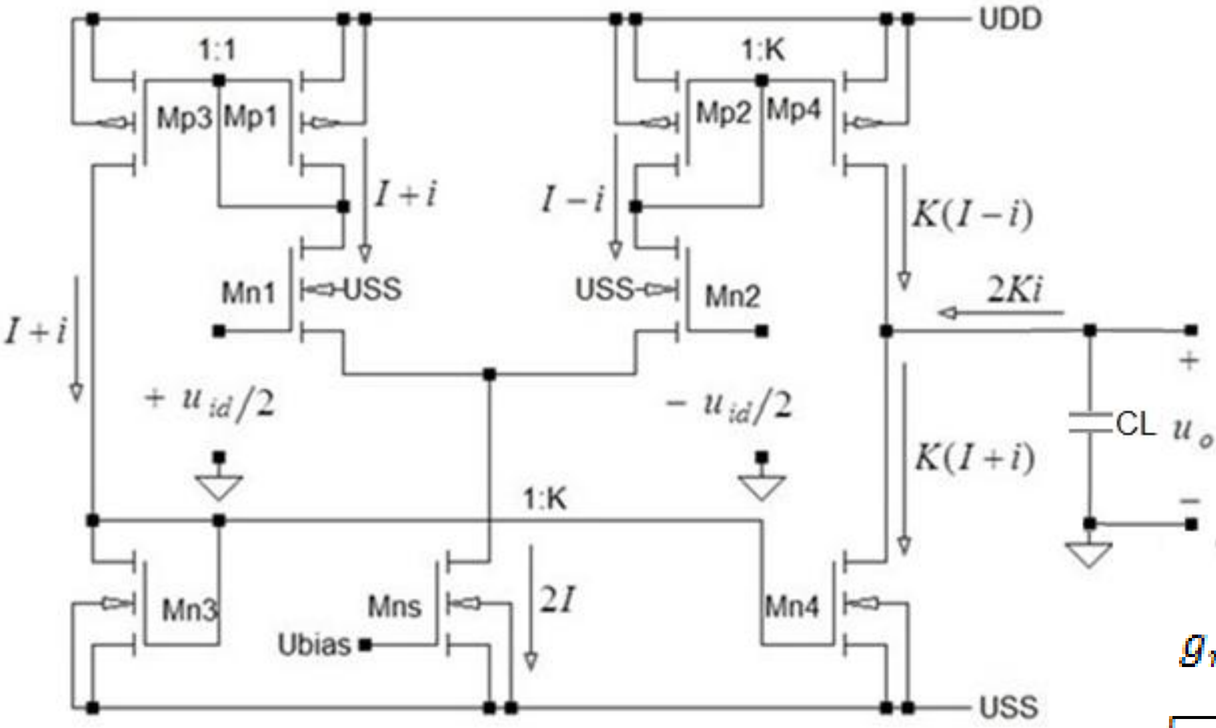


Операционни усилватели на проводимост

Характеристика на (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.

АЧХ на ОТА с просто токово огледало



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

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

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

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

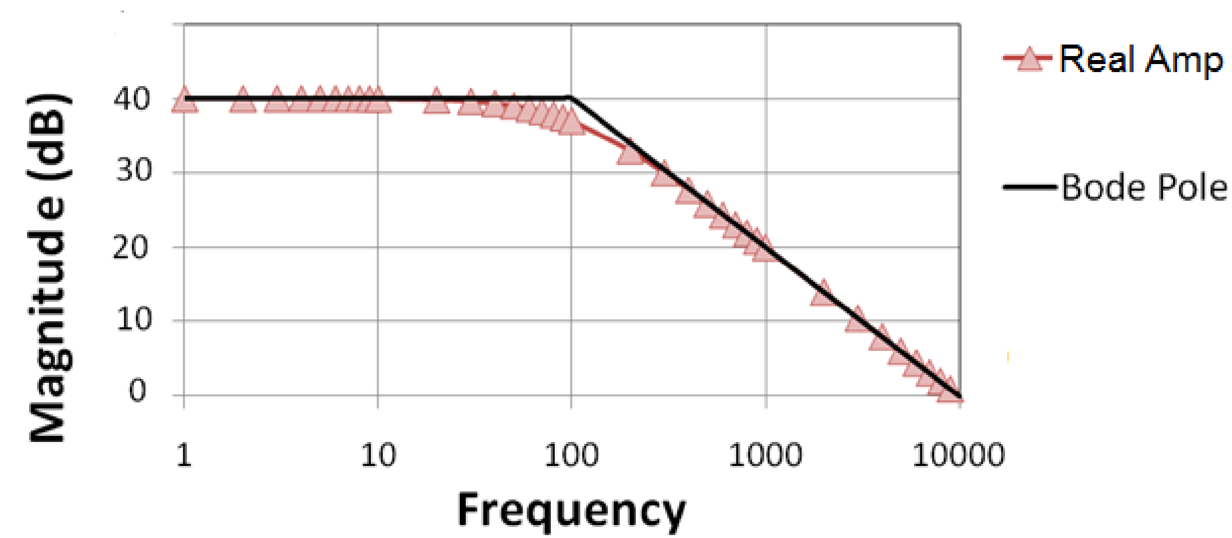
$$g_{mn1} = \sqrt{2\mu_n C_{ox} {}^{W1}/_{L1} I} = \frac{2I}{U_{eff}}$$

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

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

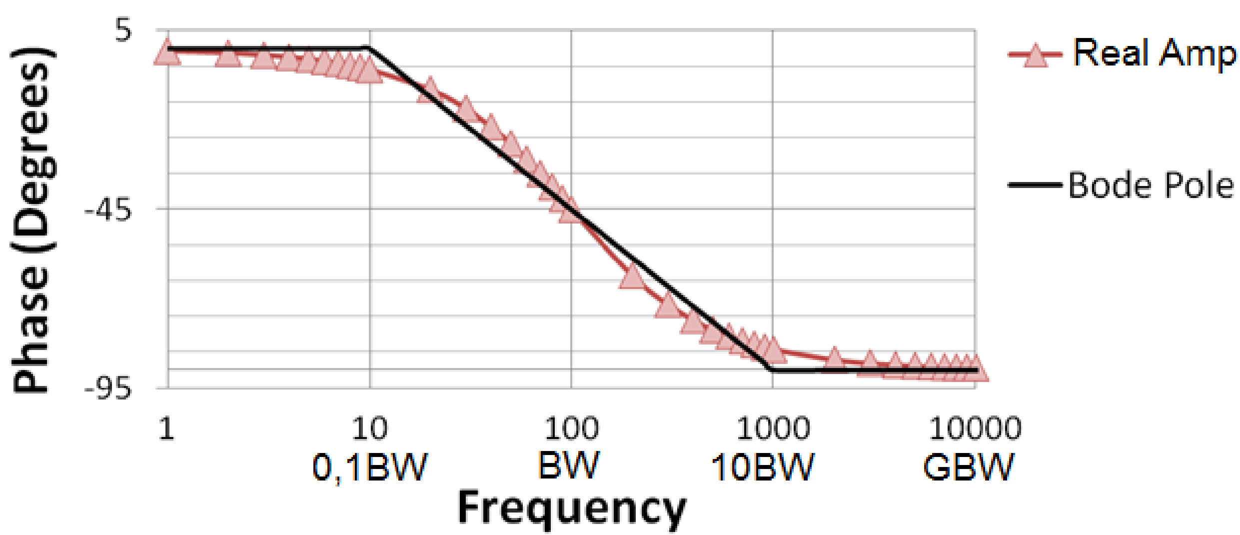
$$SR = \frac{2KI}{C_L}$$

Диаграми на Боде

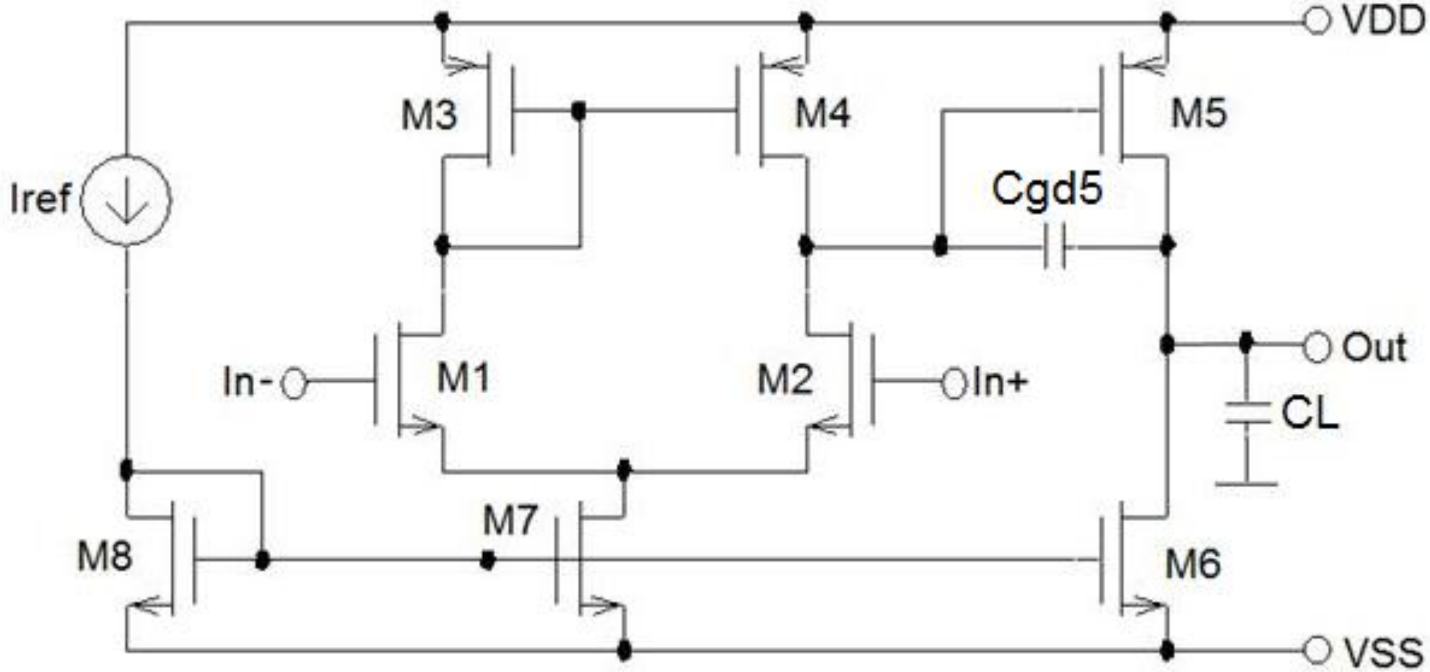


$$\text{Phase} = -\text{arctg}\frac{f}{f_\beta}$$

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



OTA на Милер



$$A_{ud} = A_{ud1} A_{ud2}$$

$$f_p = \frac{1}{2\pi r_{out} C}$$

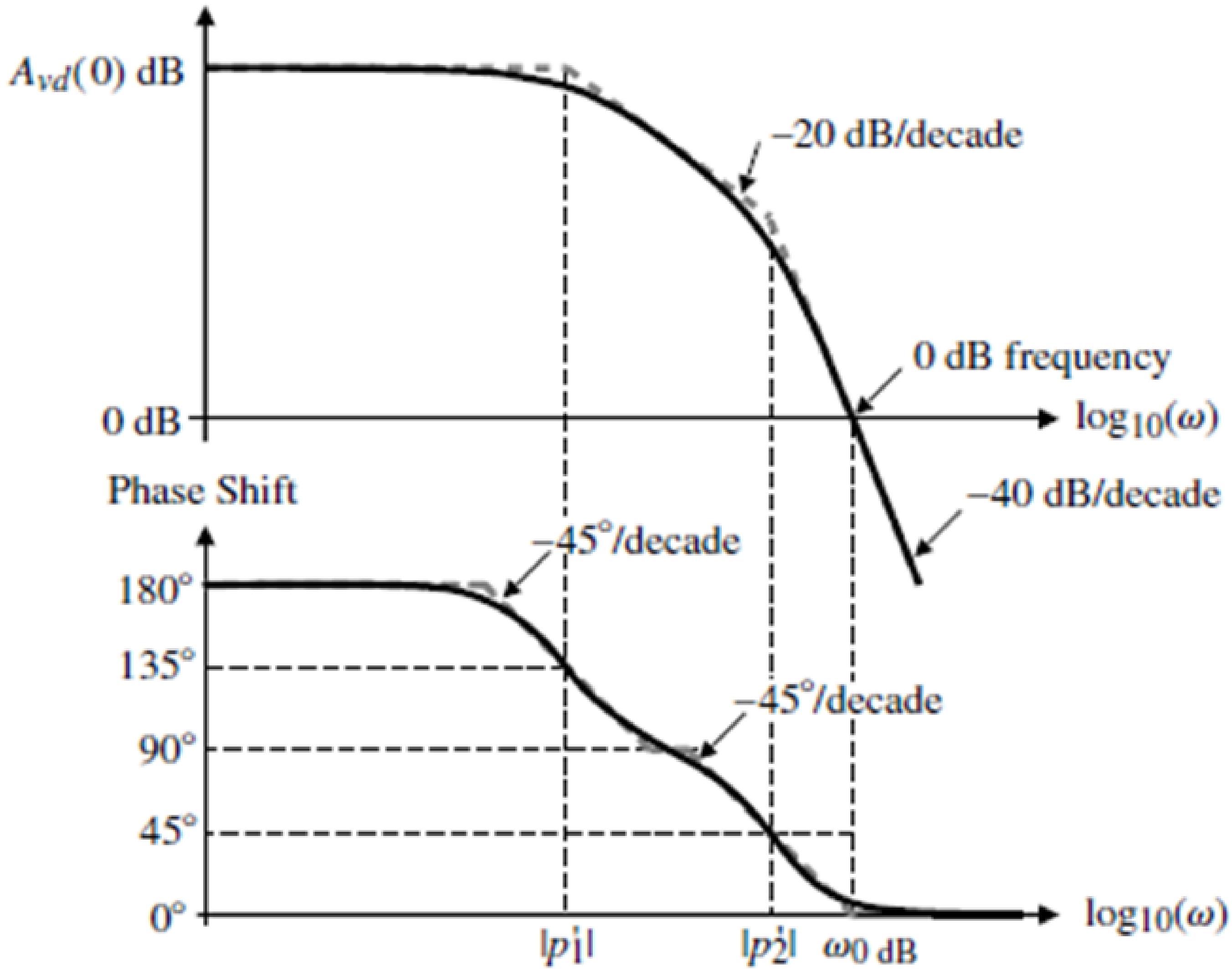
$$A_{ud1} = -\frac{g_{mn2}}{g_{dsn2} + g_{dsp4}} \qquad A_{ud2} = -\frac{g_{mp5}}{g_{dsp5} + g_{dsn6}}$$

$$f_{p1} = \frac{g_{dsp4} + g_{dsn2}}{2\pi (A_{ud2} + 1) C_{gd5}}$$

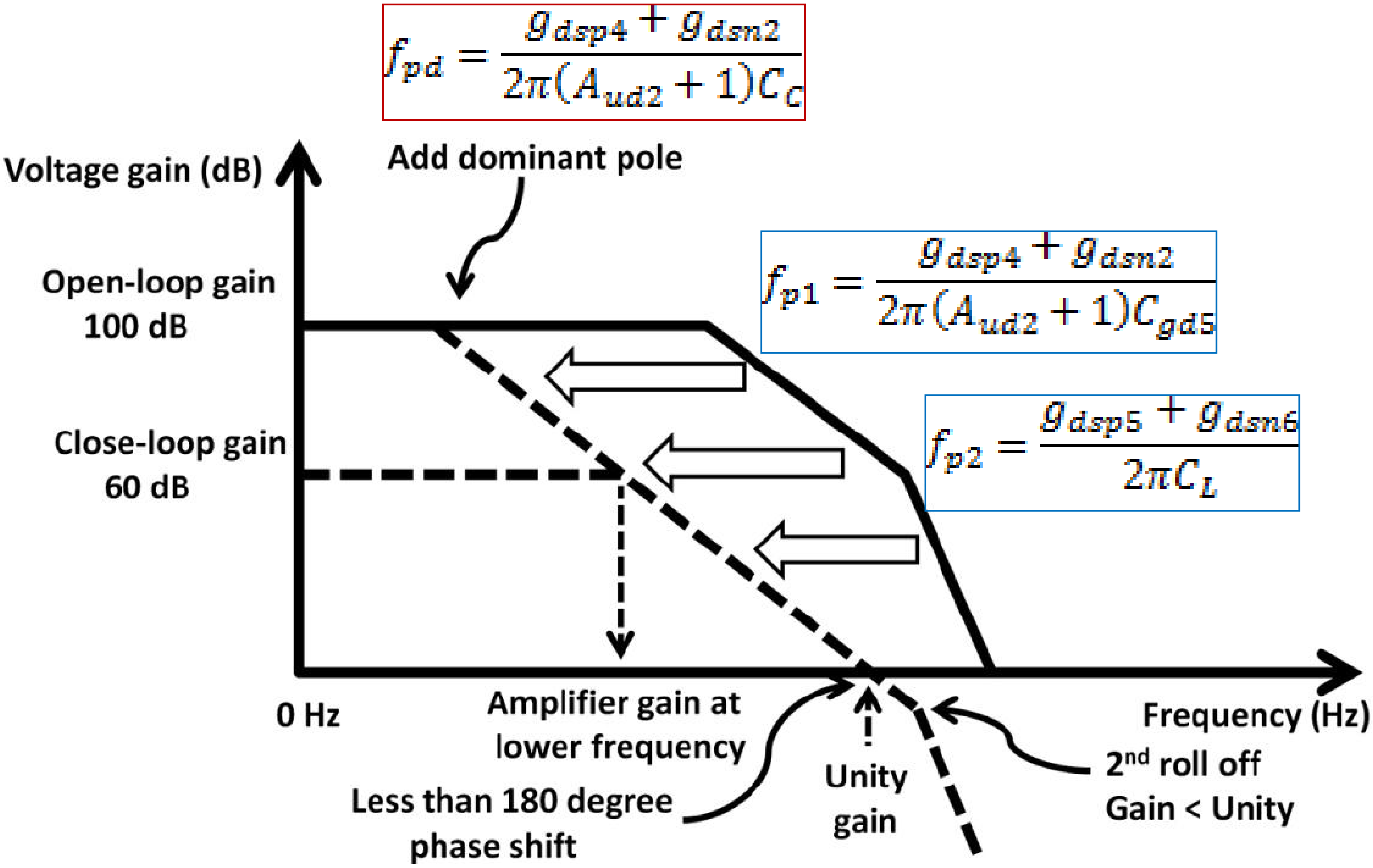
$$A_{ud} = A_{ud1} A_{ud2} = \frac{g_{mn2}}{g_{dsn2} + g_{dsp4}} \frac{g_{mp5}}{g_{dsp5} + g_{dsn6}}$$

$$f_{p2} = \frac{g_{dsp5} + g_{dsn6}}{2\pi C_L}$$

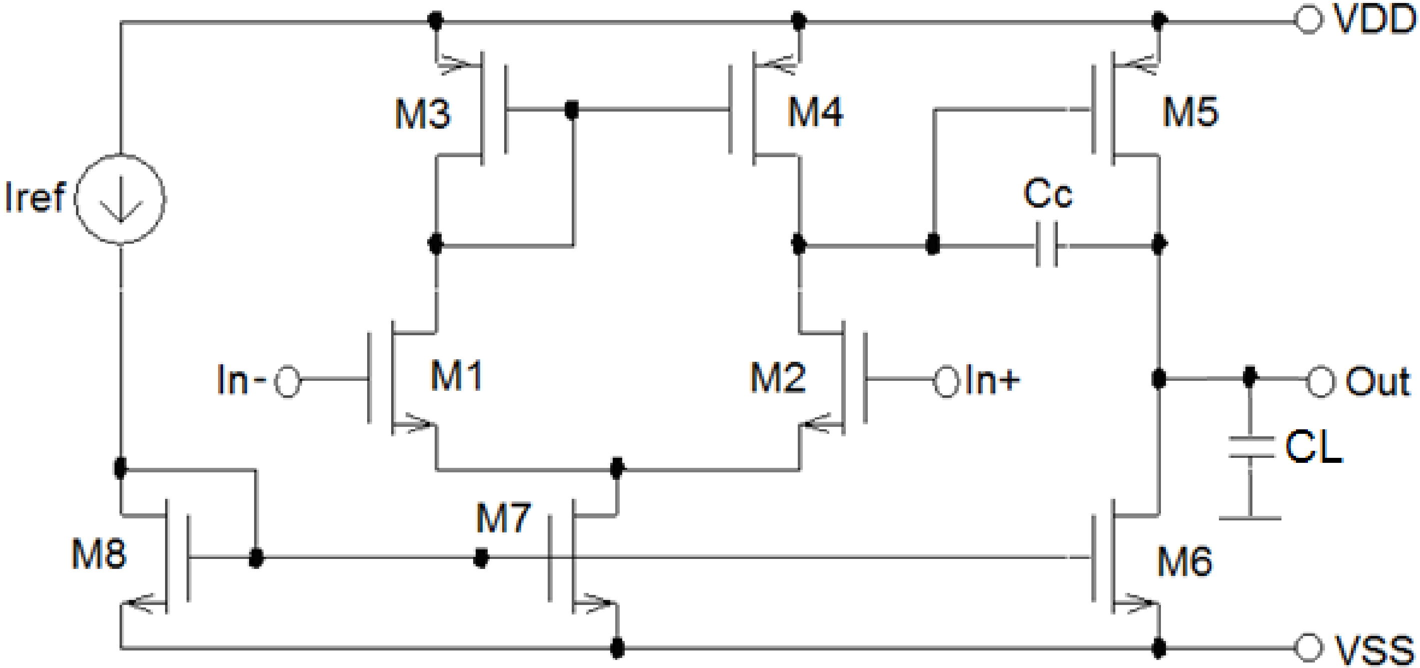
ОТА на Милер – АЧХ и ФЧХ без компенсация



ОТА на Милер – честотна компенсация



ОТА на Милер - честотна компенсация

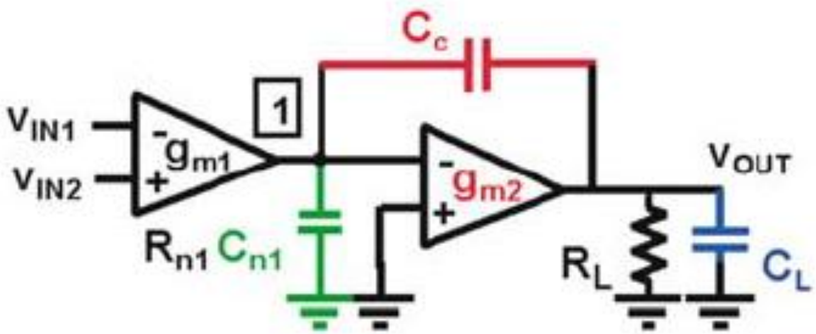


$$BW = f_{pd} = \frac{g_{dsp4} + g_{dsn2}}{2\pi(A_{ud2}+1)C_C} \qquad f_{nd} \approx \frac{g_{mp5}}{2\pi C_L} \qquad f_z = \frac{g_{mp5}}{2\pi C_c}$$

(положителна нула!)

$$GBW = |Au1||Au2|BW = \left|\frac{g_{mn2}}{g_{dsn2}+g_{dsp4}}\right|\left|\frac{g_{mp5}}{g_{dsn6}+g_{dsp5}}\right|\frac{g_{dsn2}+g_{dsp4}}{2\pi(A_{ud2}+1)C_C} \approx \frac{g_{mn2}}{2\pi C_C}$$

Общ случай на положителна нула



$$A_{v0} = - A_{v1} A_{v2}$$

$$A_{v1} = g_{m1} R_{n1}$$

$$A_{v2} = g_{m2} R_L$$

$$A_v = A_{v0} \frac{1 - \frac{C_c}{g_{m2}} s}{1 + (R_{n1}C_{n1} + A_{v2}R_{n1}C_c + R_L C_L)s + R_{n1}R_L CC s^2}$$

$$CC = C_{n1}C_c + C_{n1}C_L + C_c C_L$$

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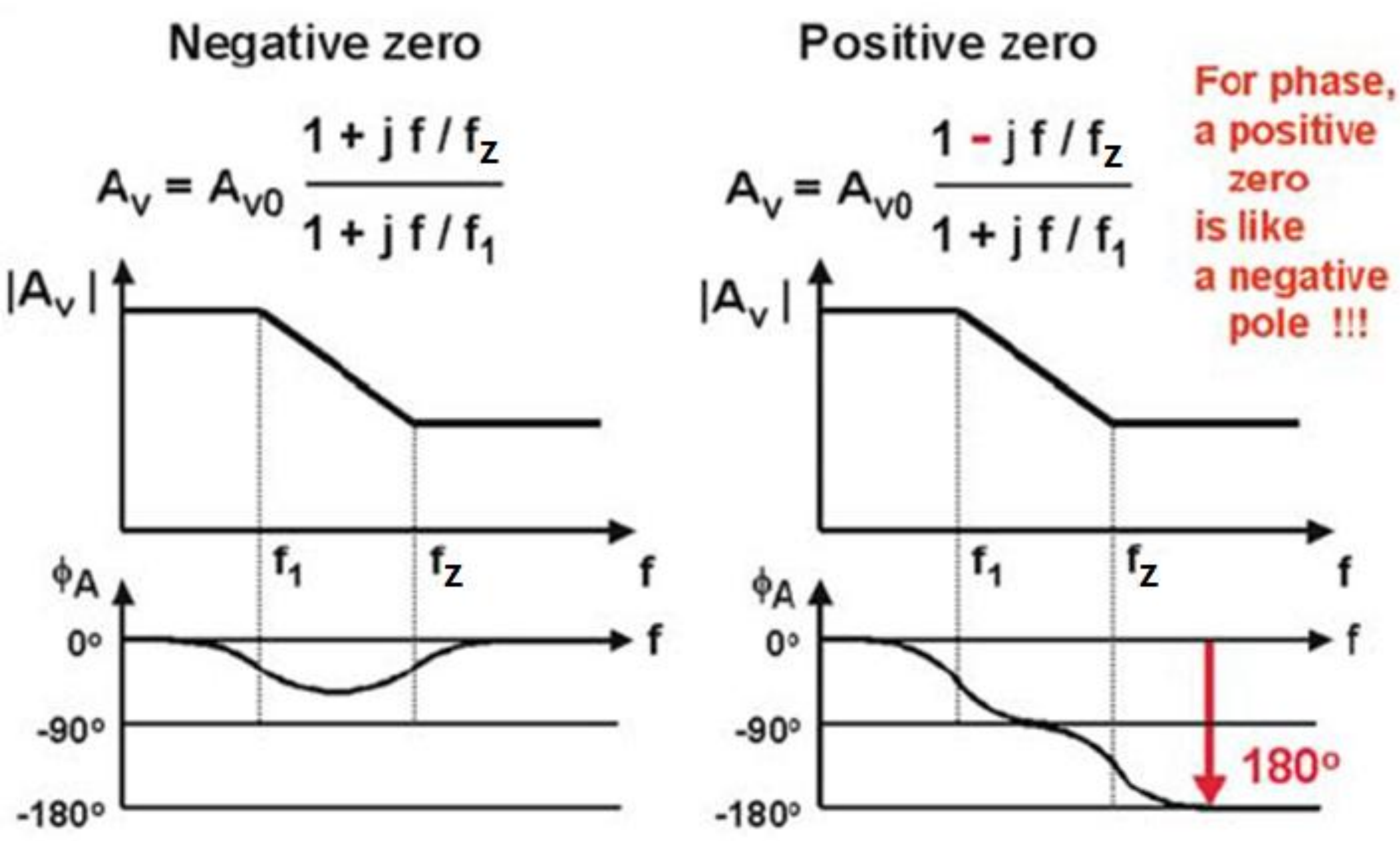
$$A = A_0 \frac{1 - cs}{1 + a\,s + b\,s^2}$$

Pole $s_1 = -\frac{1}{a}$

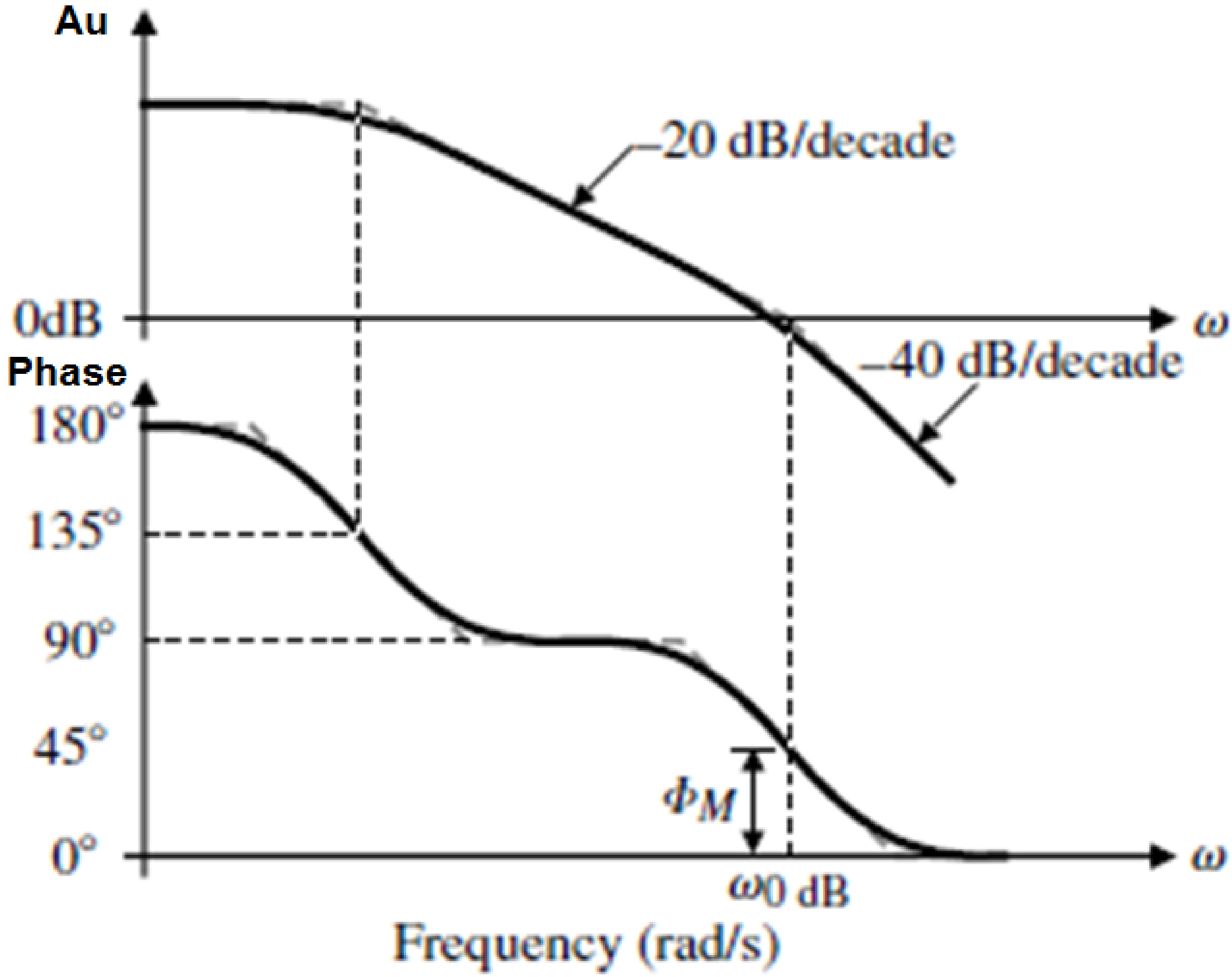
Zero $s = \frac{1}{c}$

$s_2 = -\frac{a}{b}$ if $s_2 >> s_1$

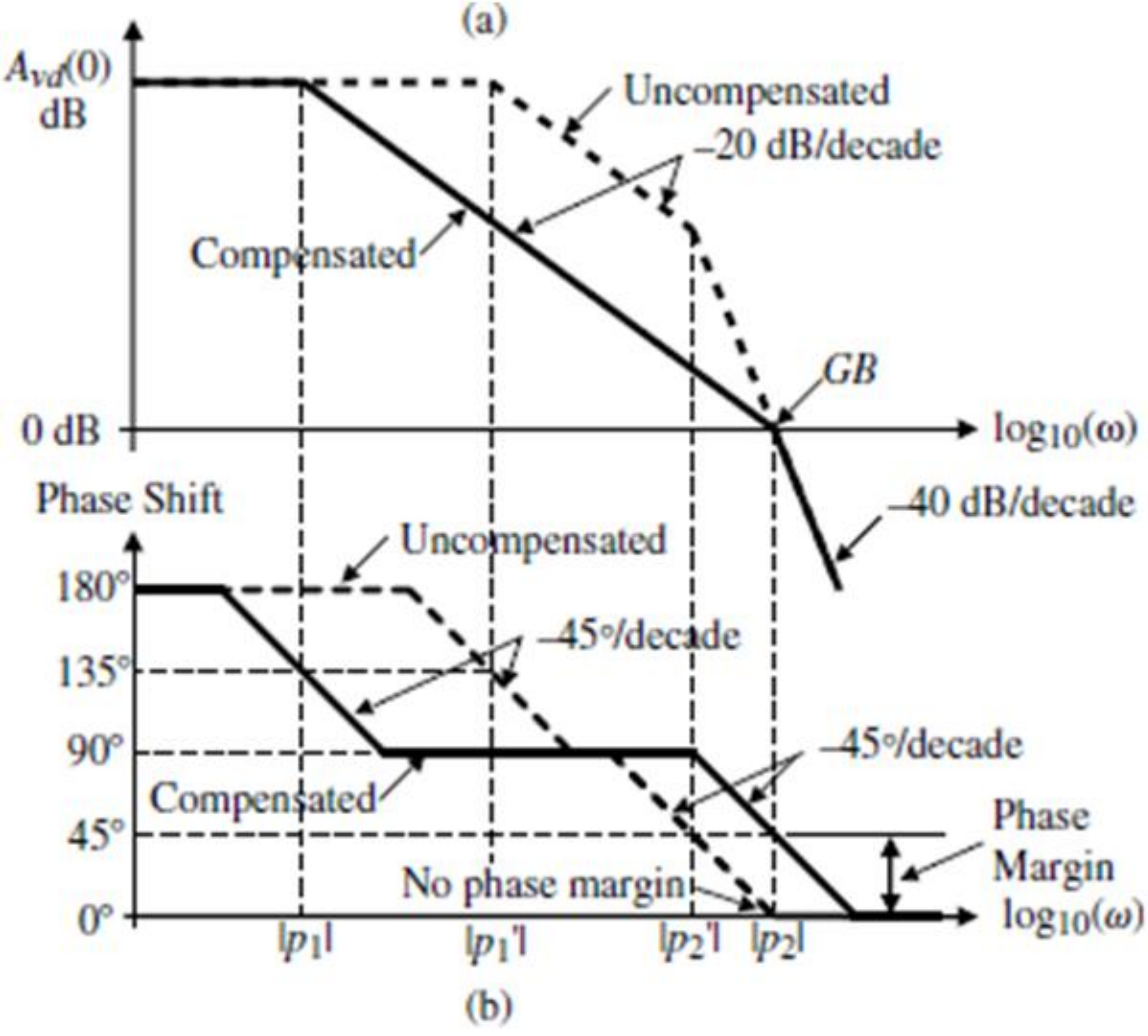
Ефект на положителната нула (пример със система от първи ред)



АЧХ и ФЧХ при честотна компенсация



Честотна компенсация - основни зависимости



$$f_z > 10GBW$$

$$\frac{g_{mp5}}{2\pi C_c} > 10\frac{g_{mn2}}{2\pi C_c}$$

$$g_{mp5} > 10 g_{mn2}$$

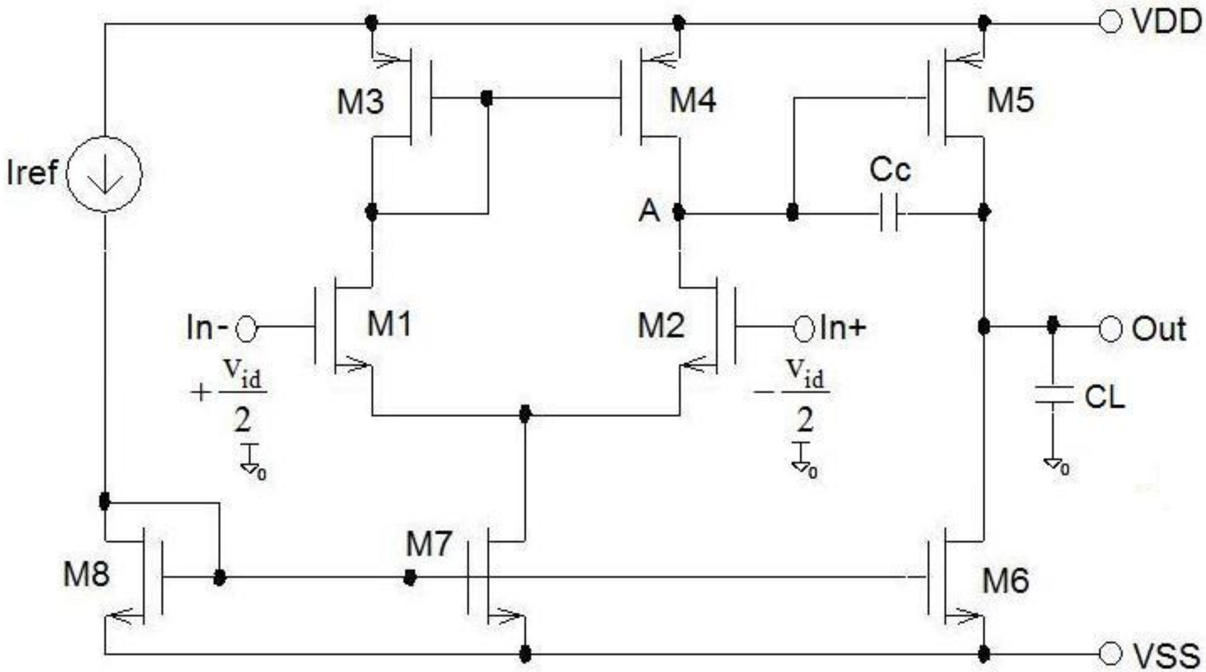
$$FM = 60^\circ$$

при $f_{nd}(f_{p2}) > 2{,}2GBW$

$$\frac{g_{mp5}}{C_L} > 2{,}2\frac{g_{mn2}}{C_c}$$

$$C_c > 2{,}2\frac{C_L}{10}$$

ОТА на Милер - обобщение



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

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

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

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

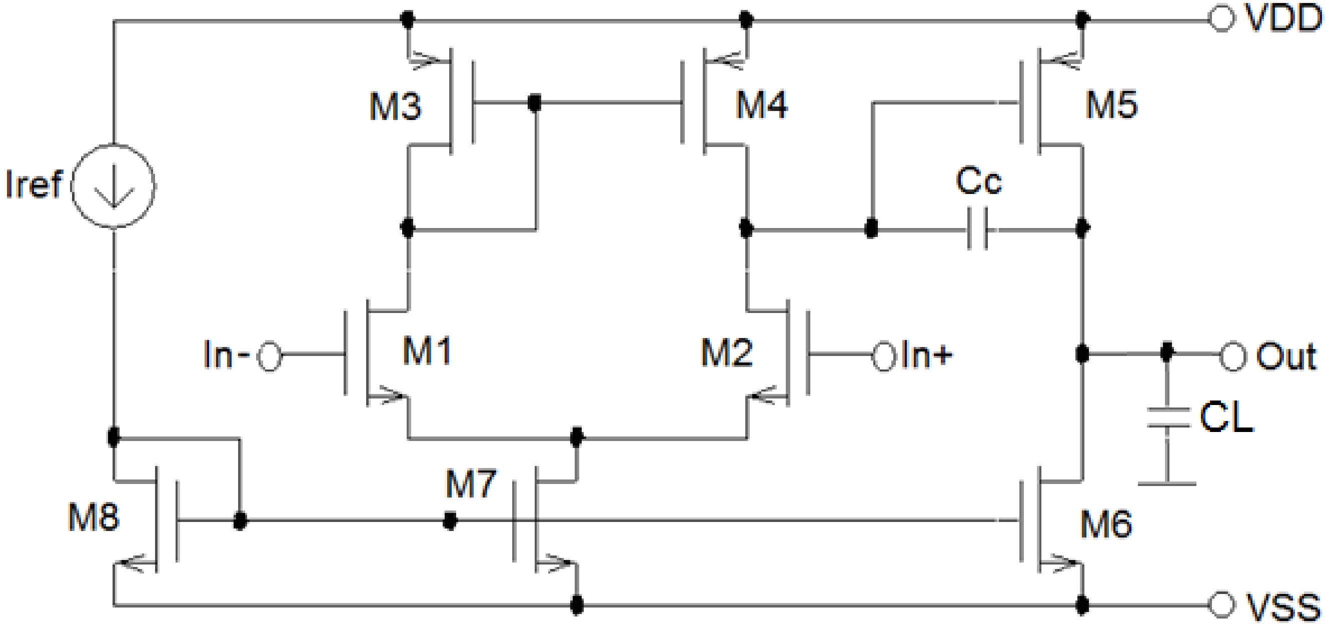
$$r_{out} = \frac{1}{g_{dsp5} + g_{dsn6}}$$

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

$$BW = \frac{1}{2\pi r_{out} A_{u2} C_c}$$

$$BW = \frac{(g_{dsp4} + g_{dsn2}) \cdot (g_{dsn6} + g_{dsp5})}{2\pi g_{mp5} C_c}; \qquad GBW = \frac{g_{mn2}}{2\pi C_c}; \qquad SR = \frac{I_{D7}}{C_c}$$

ОТА 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:

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

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

ОТА на Милер – формули за изчисление

при $f_{nd}(f_{p2}) > 2{,}2GBW$ $\quad FM = 60^{\circ}$ $\quad C_c > 2{,}2\dfrac{C_L}{10}$

$$GBW = |Au1||Au2|BW = \left|\frac{g_{mn2}}{g_{dsn2}+g_{dsp4}}\right|\left|\frac{g_{mp5}}{g_{dsn6}+g_{dsp5}}\right|\frac{g_{dsn2}+g_{dsp4}}{2\pi(A_{ud2}+1)C_C} \approx \frac{g_{mn2}}{2\pi C_C}$$

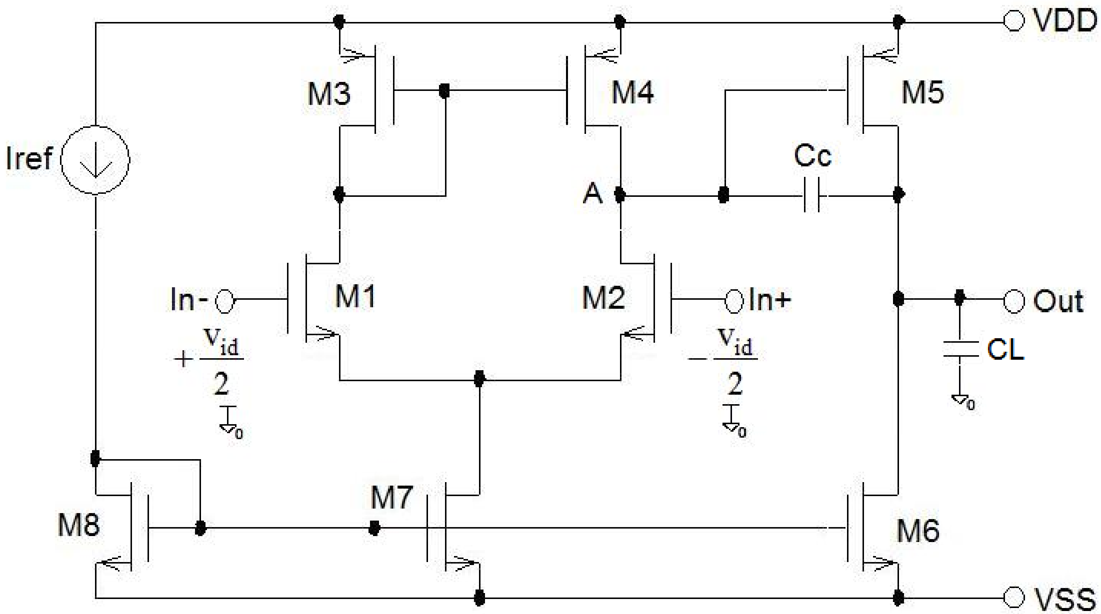
$GBW = \dfrac{g_{mn2}}{2\pi C_C}$ $\quad g_{mn2} = 2\pi C_C GBW$

$f_z > 10GBW$ $\quad \dfrac{g_{mp5}}{2\pi C_c} > 10\dfrac{g_{mn2}}{2\pi C_c}$ $\quad g_{mp5} > 10g_{mn2}$

$g_m = \dfrac{2I_D}{U_{eff}}$ $\quad I_D = \dfrac{g_m U_{eff}}{2}$

$I_D = \dfrac{K_{n(p)}}{2}\dfrac{W}{L}U_{eff}^2$ $\quad \dfrac{W}{L} = \dfrac{2I_D}{K_{n(p)}U_{eff}^2}$

Проектиране на ОТА на Милер



Дадено:

$GBW = 1\ MHz;\ \ C_L = 10pF$

Изчисления:

$$C_c > 2{,}2\frac{C_L}{10} = 2{,}2\frac{10pF}{10} = 2{,}2pF$$

Избираме $C_C = 2{,}5pF$

$$g_{mn2} = 2\pi C_C GBW = 15{,}7\ \mu A/V$$

Избираме $g_{mn2} = 18\ \mu A/V$

$$g_{mp5} > 10 g_{mn2} = 180\ \mu A/V$$

Избираме $g_{mp5} = 250\ \mu A/V$

$$I_D = \frac{g_m U_{eff}}{2}$$

При $U_{eff} = 0{,}2\,V,\quad I_{D2} = 1{,}8\,\mu A \quad I_{D5} = 25\ \mu A$

$$I_{D1} = I_{D2} = I_{D3} = I_{D4} = I_{D8} = 1{,}8\ \mu A$$

$$I_{D5} = I_{D6} = 25\ \mu A$$

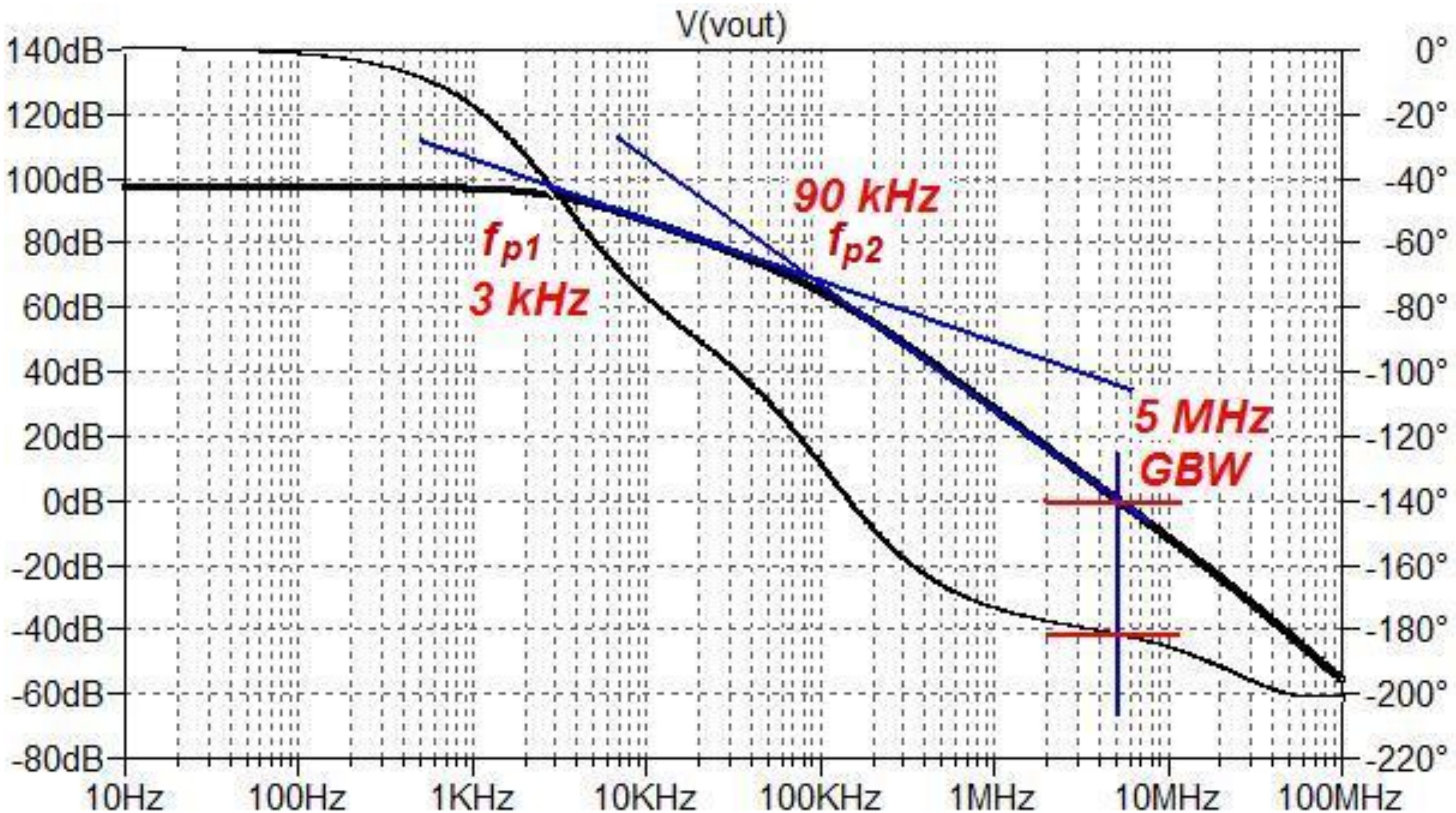
$$I_{D7} = 3{,}6\ \mu A$$

$$\frac{W1}{L1} = \frac{W2}{L2} = \frac{W8}{L8} = \frac{1{,}8}{2};\ \frac{W3}{L3} = \frac{W4}{L4} = \frac{4{,}5}{2}$$

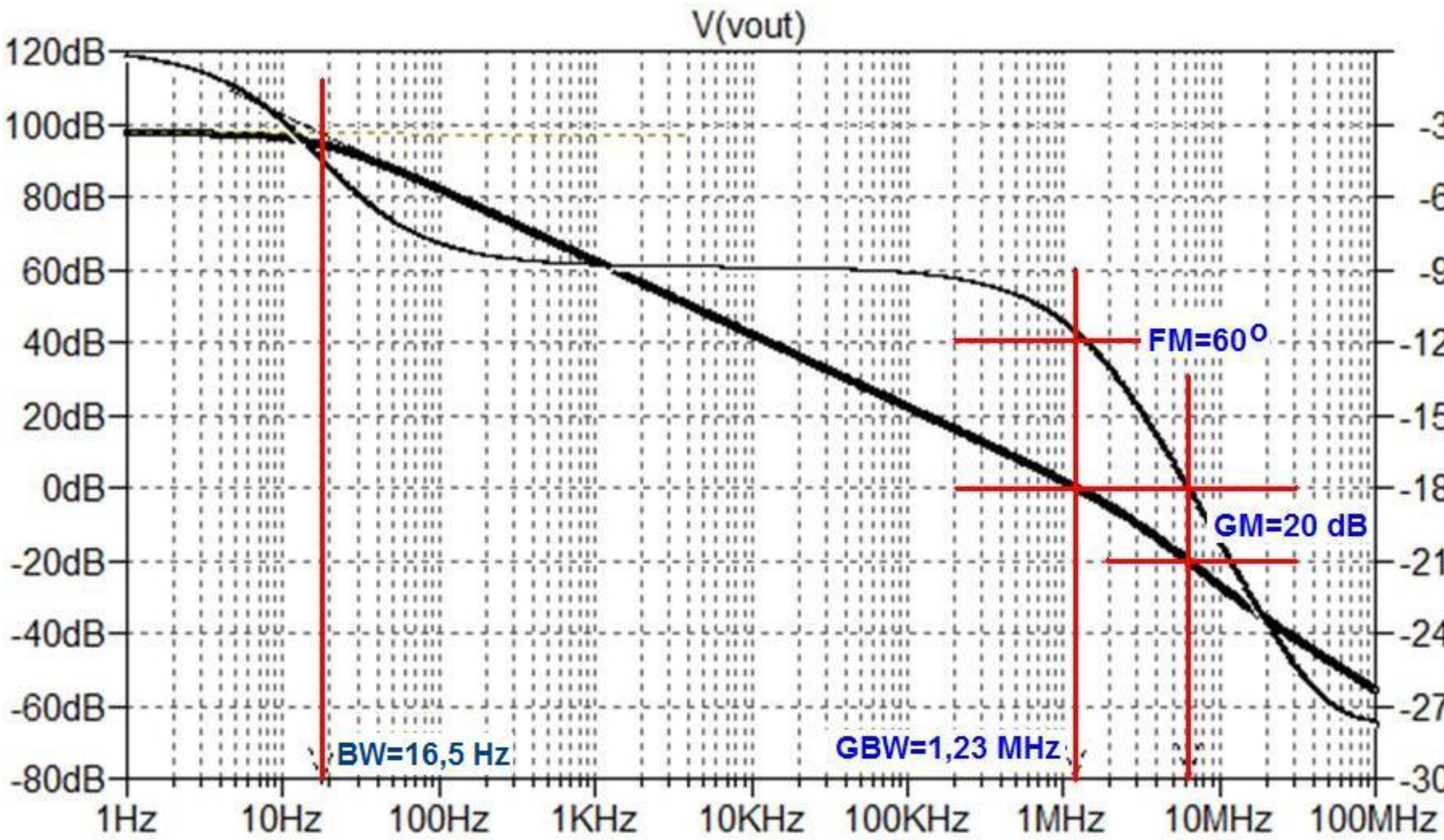
$$\frac{W6}{L6} = \frac{25}{2};\ \frac{W5}{L5} = \frac{62{,}5}{2}$$

$$\frac{W7}{L7} = \frac{3{,}6}{2}$$

АЧХ и ФЧХ без компенсация



АЧХ и ФЧХ с компенсация



Формули за определяне на основните параметри

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

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

$$GBW = \frac{g_{mn2}}{2\pi C_C} = \frac{2I_{D2}/U_{eff}}{2\pi C_C} = \frac{\sqrt{2K_n \frac{W2}{L2} I_{D2}}}{2\pi C_C}$$

$$BW = \frac{(g_{dsn2} + g_{dsp4})(g_{dsn6} + g_{dsp5})}{2\pi g_{mp5} C_C} = \frac{GBW}{A_u}$$

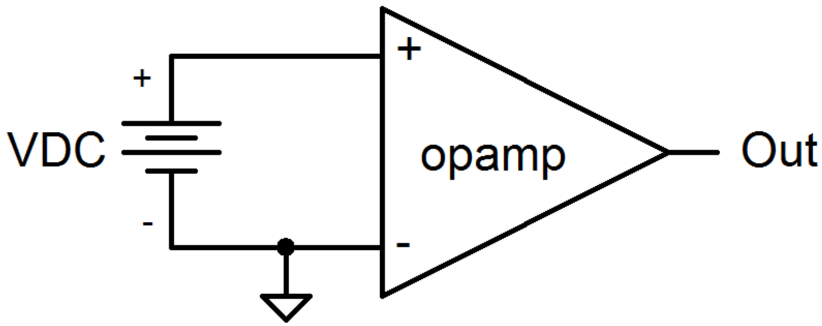
$$SR = \frac{I_{D7}}{C_C}$$

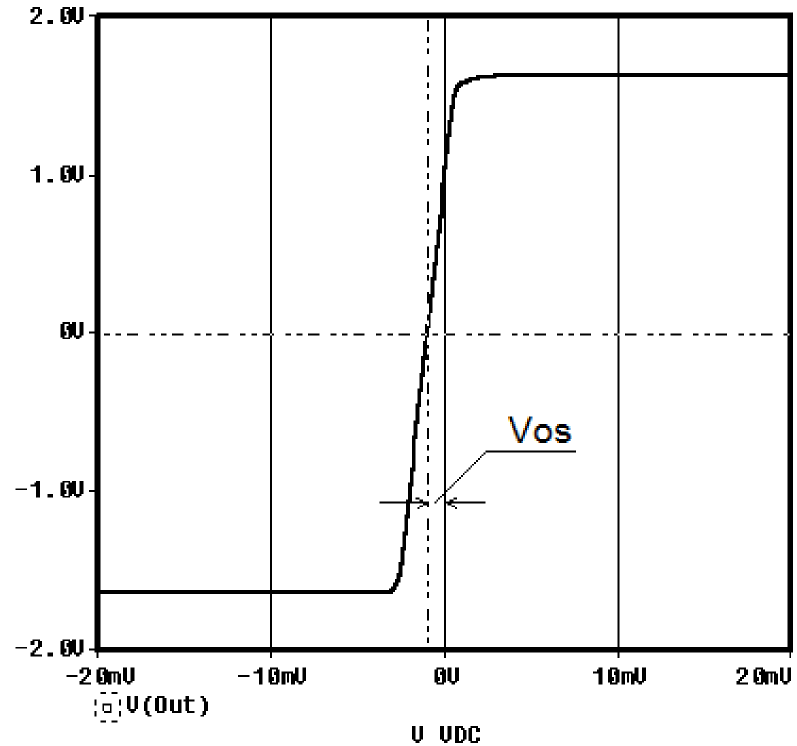
Сравнение на резултите от изчисленията и симулациите

$A_u(calc.) = 99.8dB$	$A_u(sim.) = 97.5dB$
$GBW\ (calc.) = 1{,}15MHz$	$GBW\ (sim.) = 1{,}23MHz$
$BW(calc.) = 11{,}75Hz$	$BW(sim.) = 16{,}5\ Hz$
$FM\ (design) = 60°$	$FM\ (sim.) = 63{,}7°$
$GM\ (design) = 20\ dB$	$GM\ (sim.) = 20\ dB$
$SR(calc.) = 1{,}44\ \frac{V}{\mu s}$	$SR(sim.) = 1{,}41\ \frac{V}{\mu s}$

Тестови схеми за симулиране на операционни усилватели

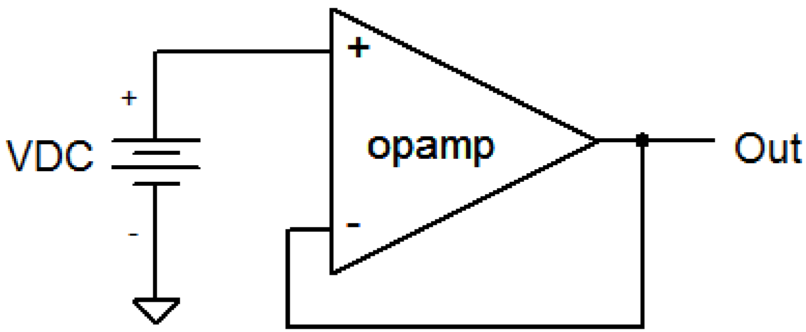
Входно напрежение на несиметрия Vos

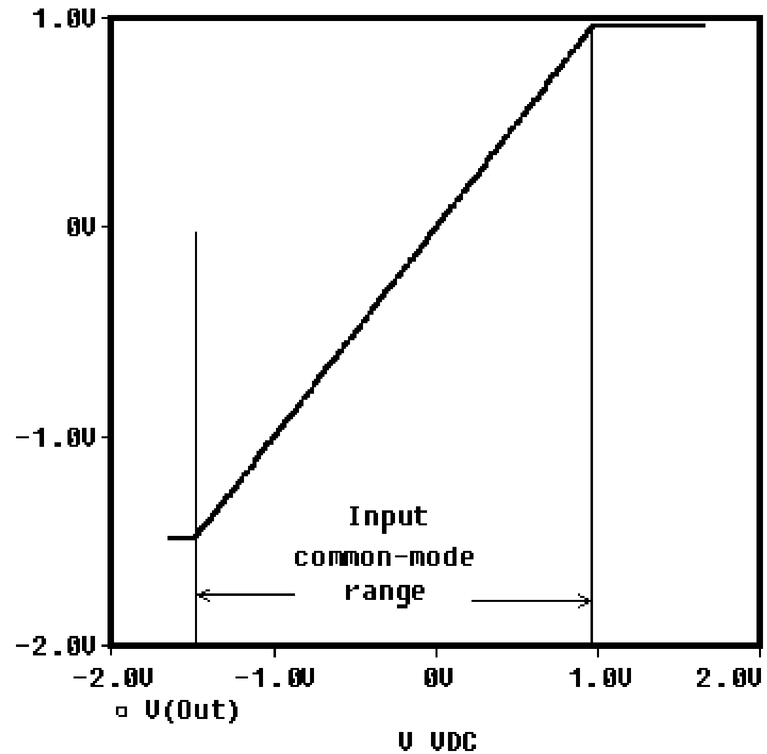




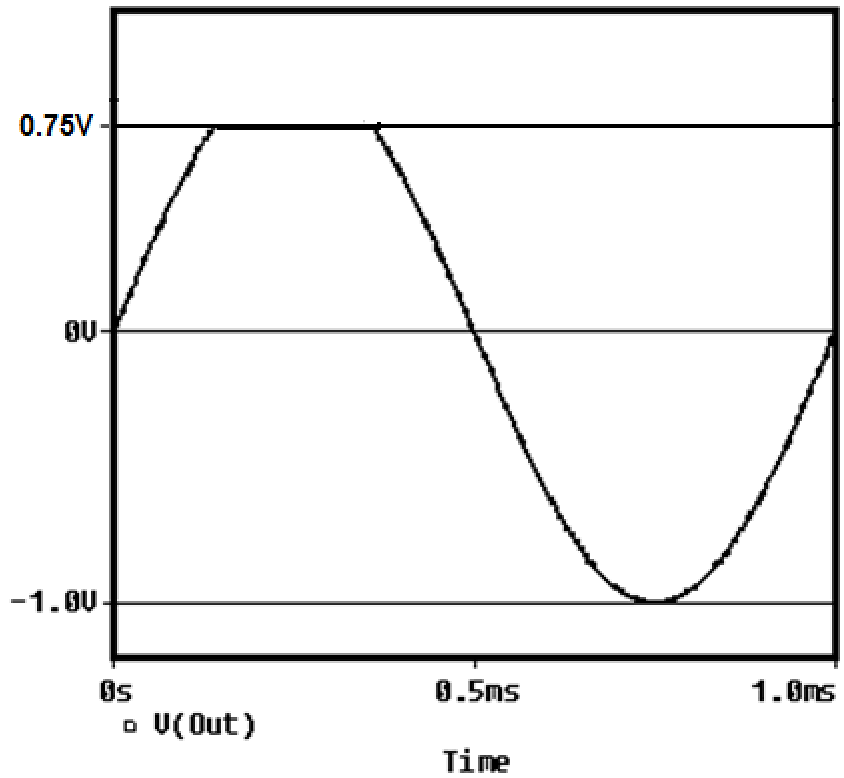
- Систематичен офсет
- Случаен офсет

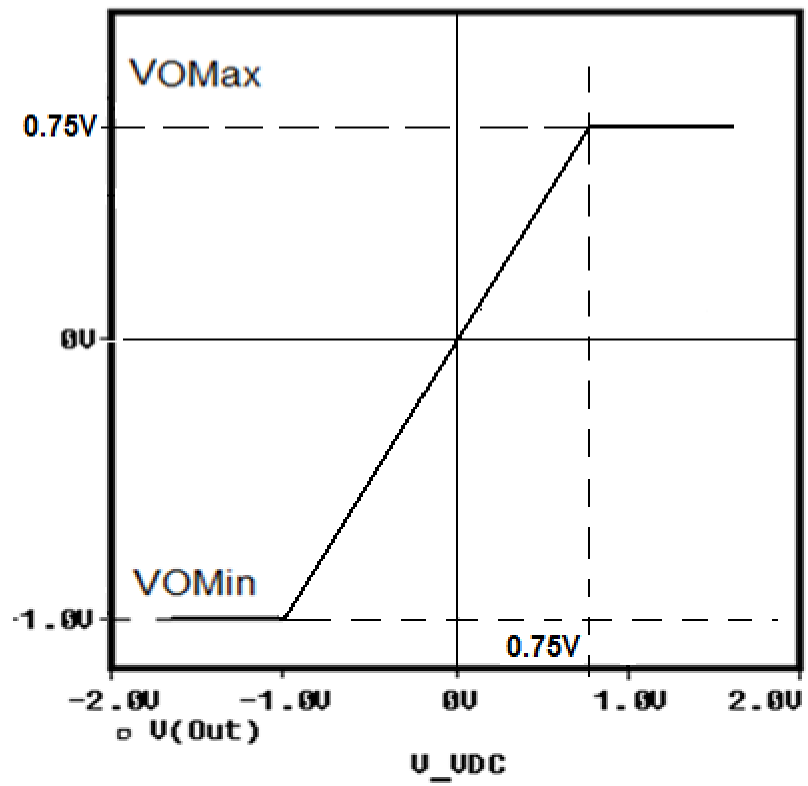
Размах на входния синфазен сигнал



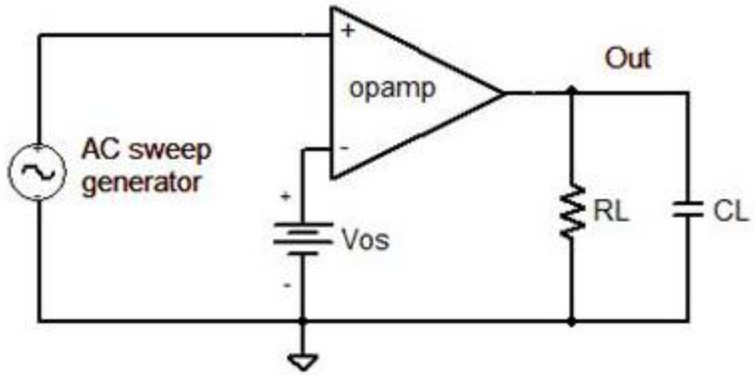


Максимален размах на изходния сигнал

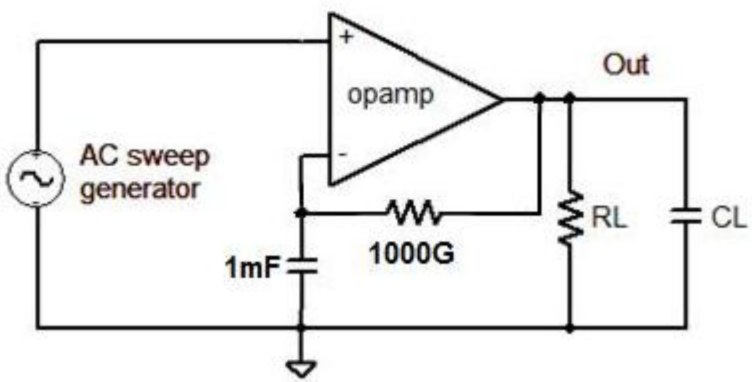




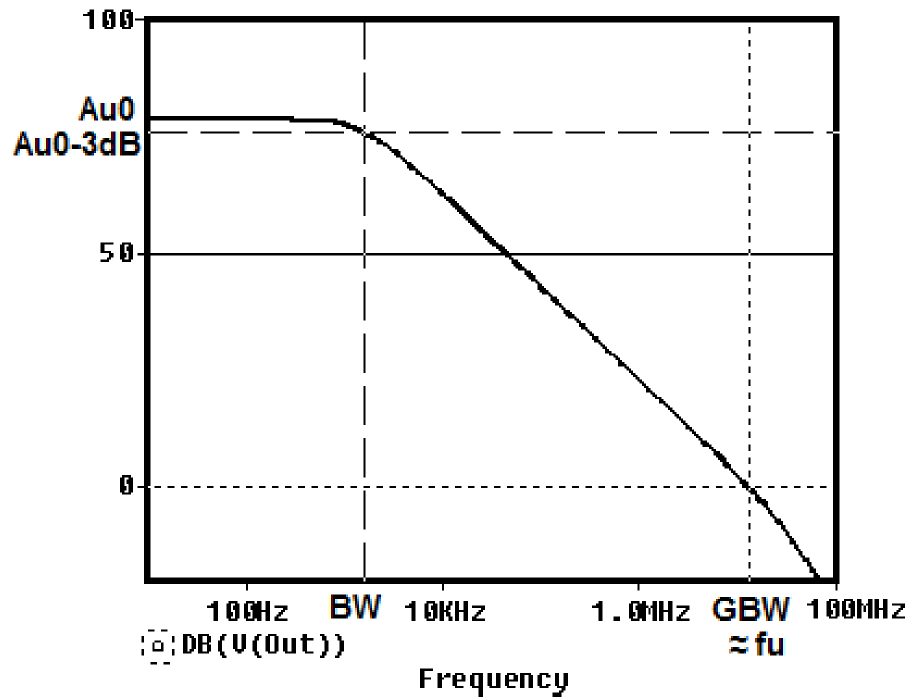
Au, BW and GBW



opamp
Out
AC sweep
generator
Vos
RL
CL

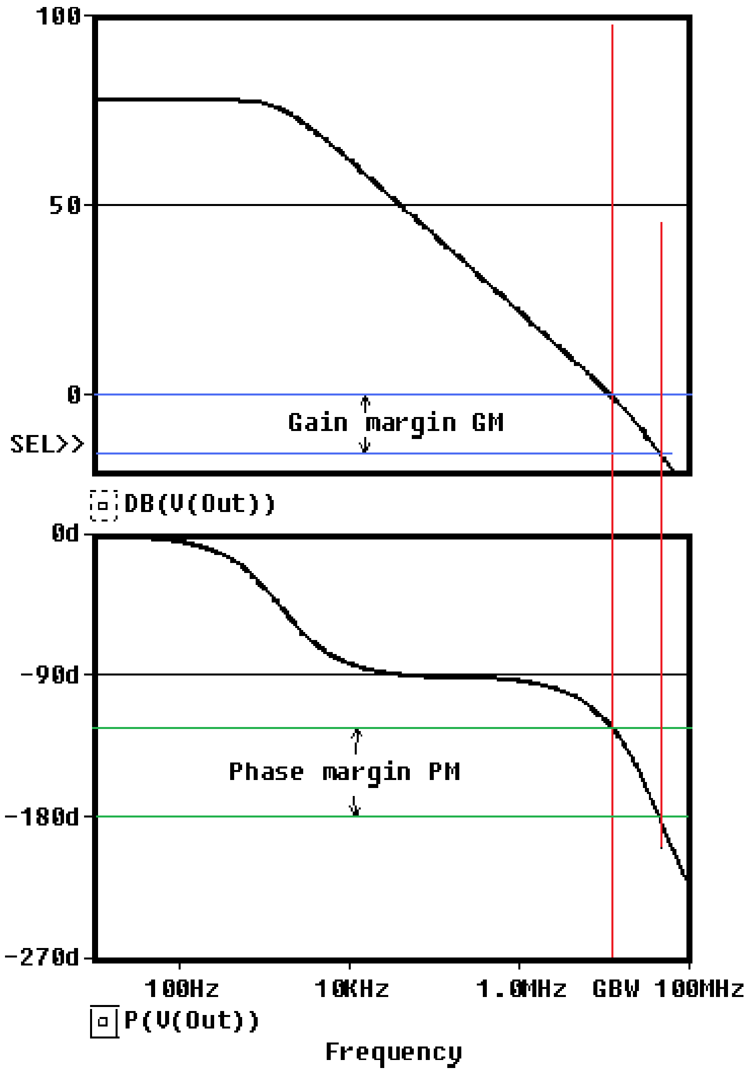


opamp
Out
AC sweep
generator
1mF
1000G
RL
CL

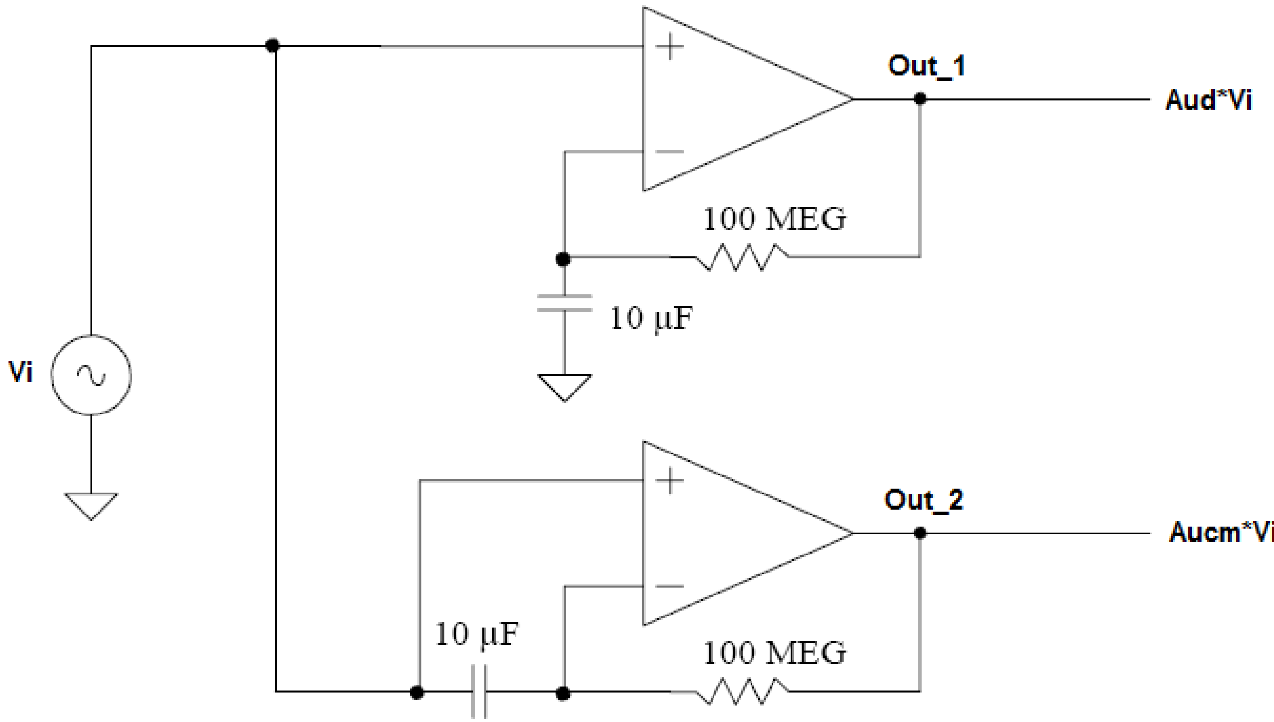


100
Au0
Au0-3dB
50
0
100Hz
BW
10KHz
1.0MHz
GBW
≈fu
100MHz
DB(V(Out))
Frequency

Запас по фаза и запас по усилване

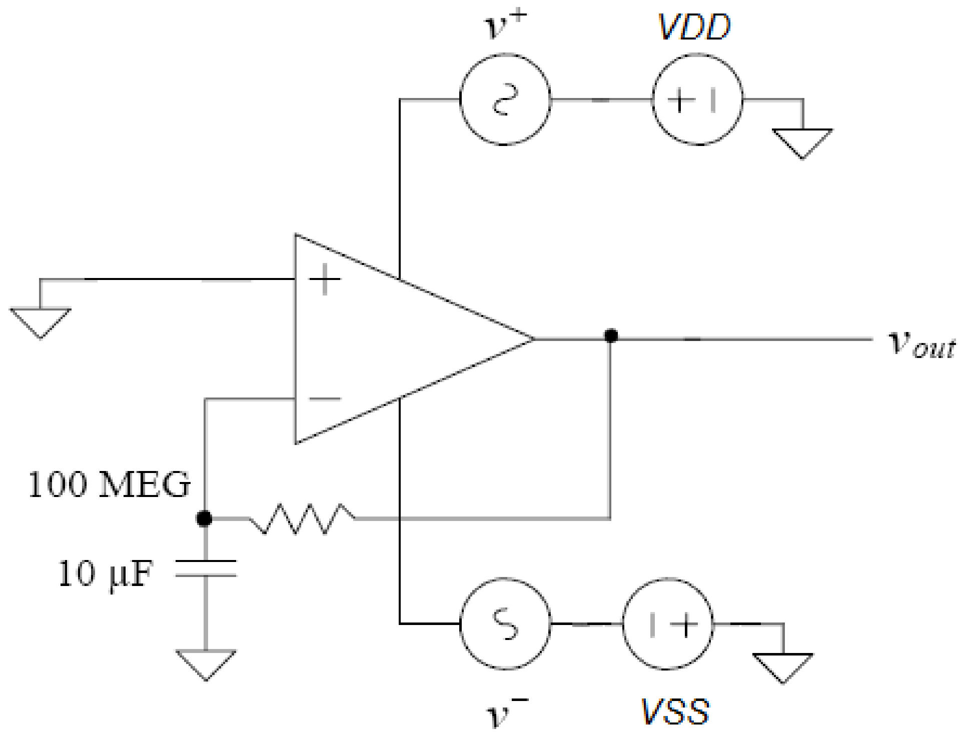


Коефициент на потискане на синфазния сигнал



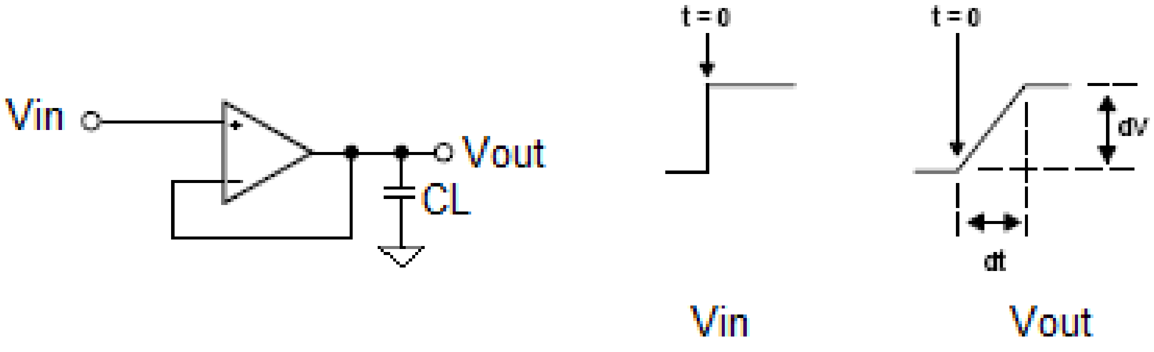
$$CMRR = 20\log\left(\frac{A_{ud}}{A_{ucm}}\right) = 20\log\left(\frac{V(Out\_1)}{V(Out\_2)}\right)$$

Коефициент на потискане на вариациите на захранващото напрежение



$$PSRR^{+} = \frac{Au}{v_{out}/v^{+}}; \quad PSRR^{-} = \frac{Au}{v_{out}/v^{-}}.$$

Скорост на нарастване на изходния сигнал



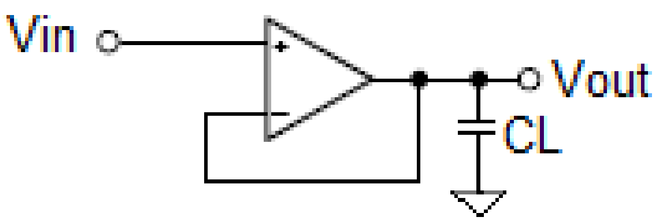
$$SR = \frac{dVout}{dt}$$

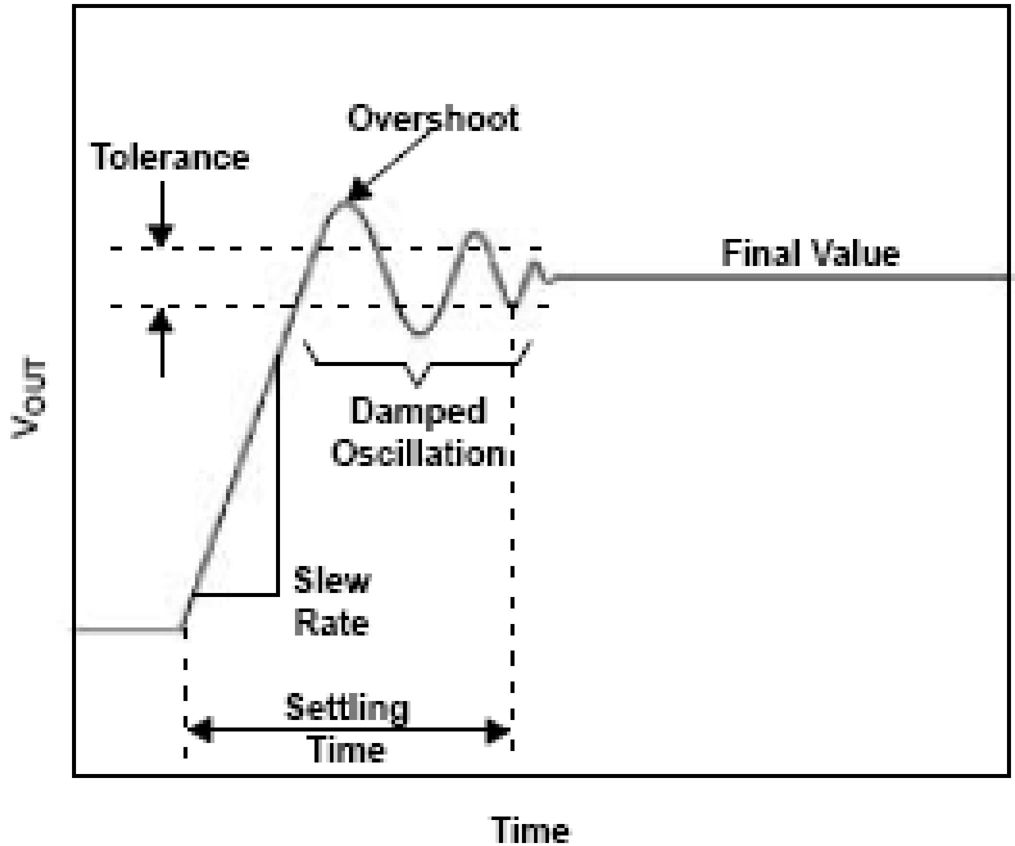
$$BOM = \frac{SR}{2\pi Vo\,min}$$

$$SR = \frac{dv_{out}}{dt} = \frac{\Delta v_{out}}{\Delta t} = \frac{I}{C_L}$$

Full-power bandwidth (FPBW) = Maximum output-swing bandwidth (BOM)

Време за установяване





Б Л А Г О Д А Р Я !