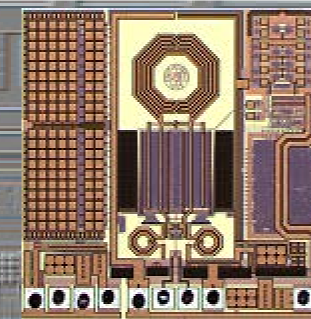

模拟集成电路设计原理

(Principle of Analog Integrated Circuit Design, INF0130025.02)

2014年11月13日

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http://rfic.fudan.edu.cn/Courses.htm

复旦大学/微电子学院/射频集成电路设计研究小组

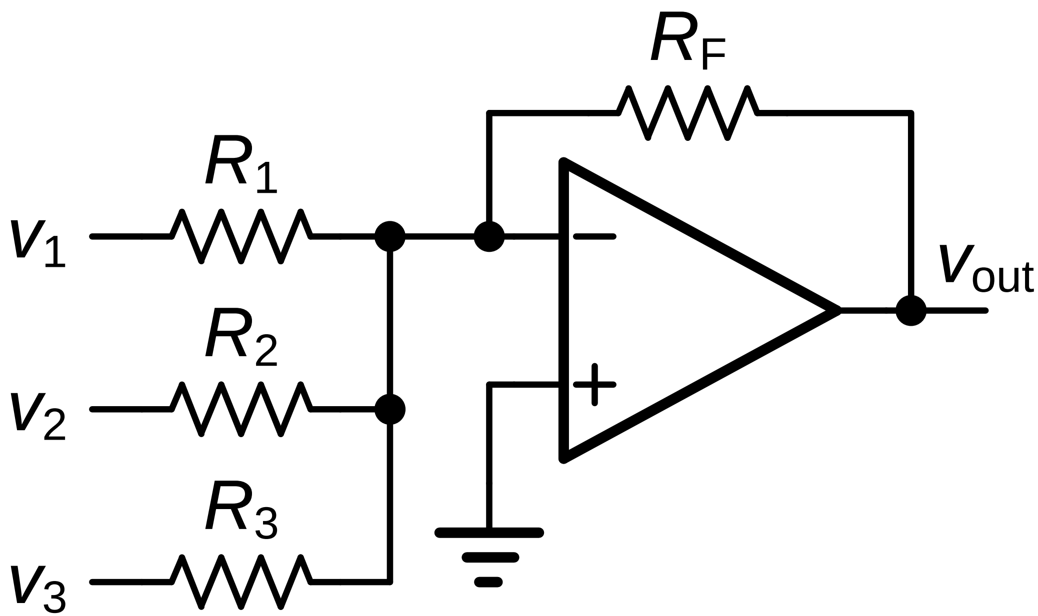
运算放大器的稳定性

目 录

- 运算放大器的使用
- 两级运放的稳定性
- 极点分离
- 正零点的补偿
- 三级运放的稳定性

Ref.: W. Sansen : Analog Design Essentials, Springer 2006

运算放大器的运算功能

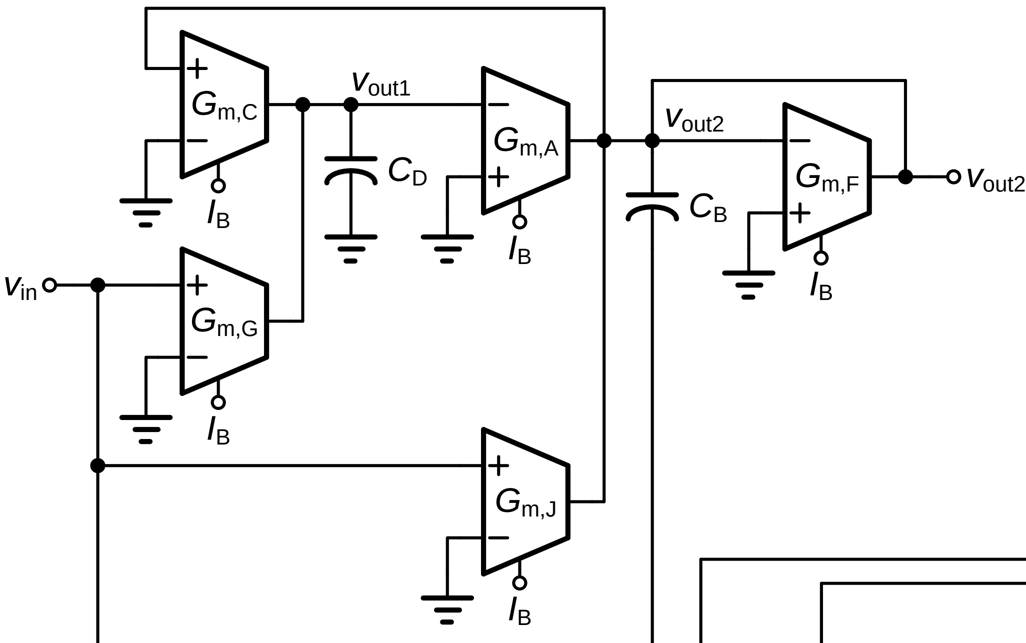


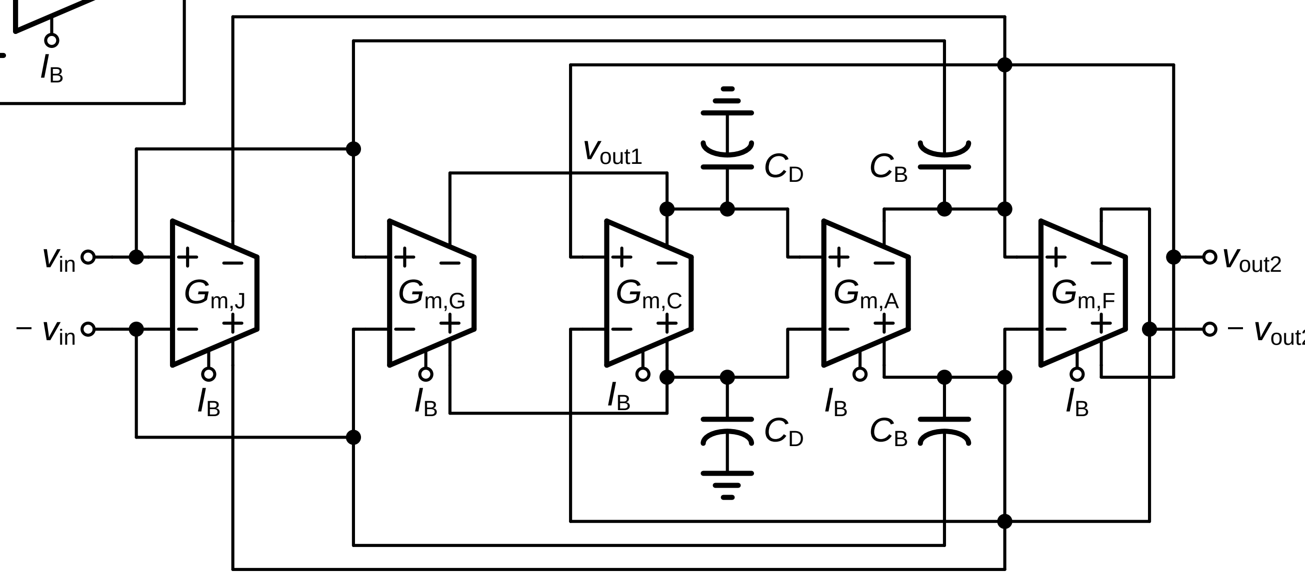
$$-\frac{v_{out}}{R_F} = \frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3}$$

要求：高增益
高速
低噪声
低功耗

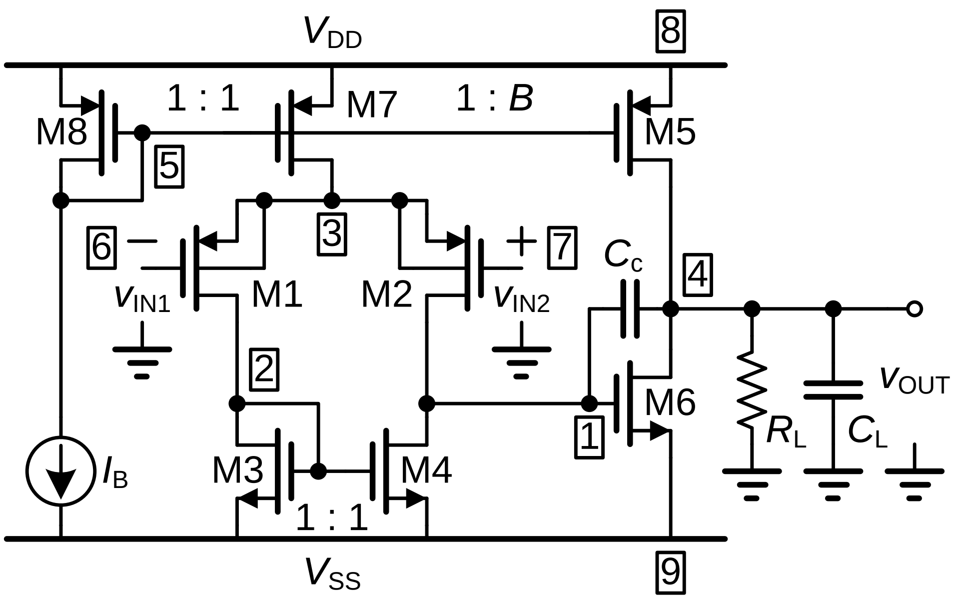
运放性能指标：高电压增益
差分输入电压≈0
输入电流 =0
高带宽
增益带宽乘积GBW非常，非常高！

单端？全差分？

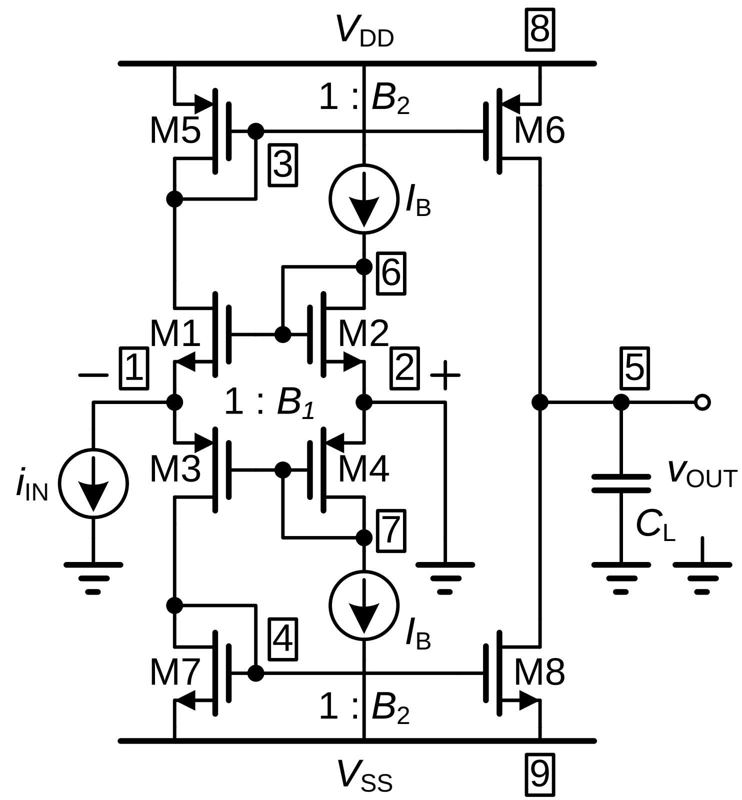

Gm,C
vout1
Gm,A
vout2
Gm,F
vout2
CD
CB
IB
vin
Gm,G
Gm,J


vout1
CD
CB
vin
− vin
Gm,J
Gm,G
Gm,C
Gm,A
Gm,F
vout2
− vout2
IB

电压输入？电流输入？



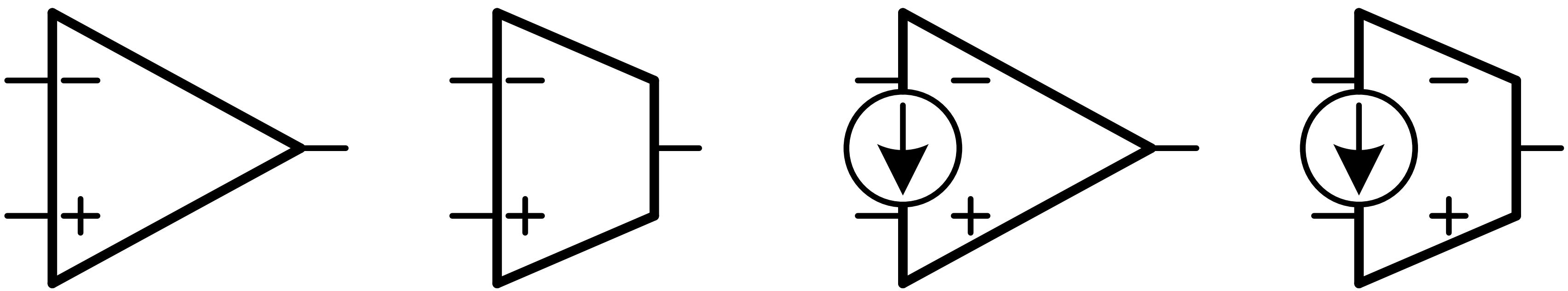
电压输入
电流输出



电流输入
电流输出

分类

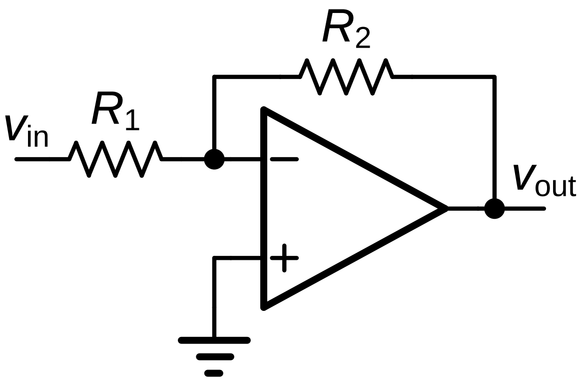
Opamp 电压放大器 | OTA 跨导放大器 | OCA 电流放大器 | CM amp 跨阻放大器

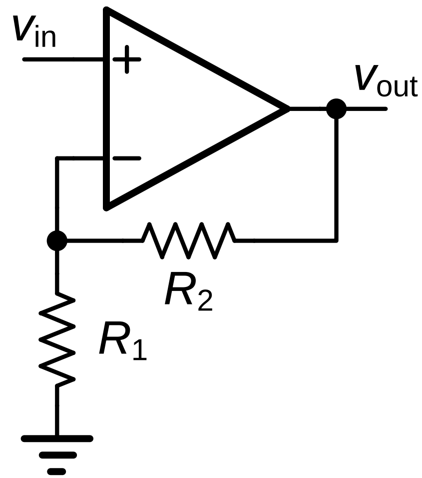


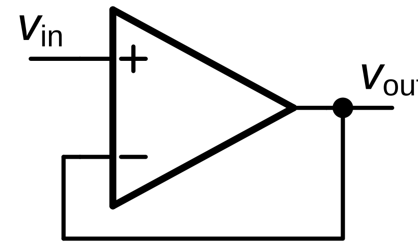
$$A_V = \frac{v_{out}}{v_{in}} \qquad A_G = \frac{i_{out}}{v_{in}} \qquad A_I = \frac{i_{out}}{i_{in}} \qquad A_R = \frac{v_{out}}{i_{in}}$$

$$A_V = GBW \qquad A_V = A_G R_L \qquad A_V = A_I \frac{R_L}{R_S} \qquad A_V = A_R \frac{1}{R_S}$$

反馈结构







$$A_V = -\frac{R_2}{R_1}$$

$$R_{IN} = R_1$$

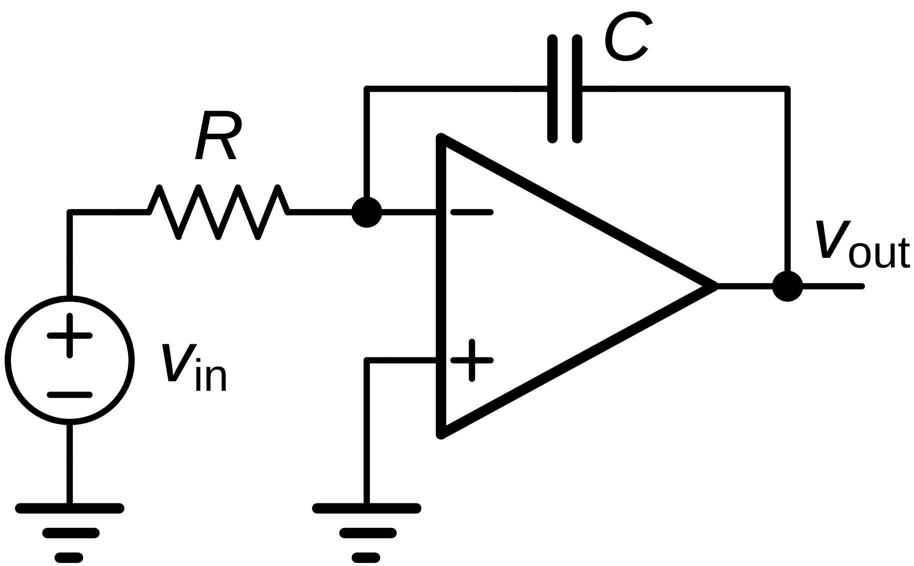
$$A_V = 1 + \frac{R_2}{R_1}$$

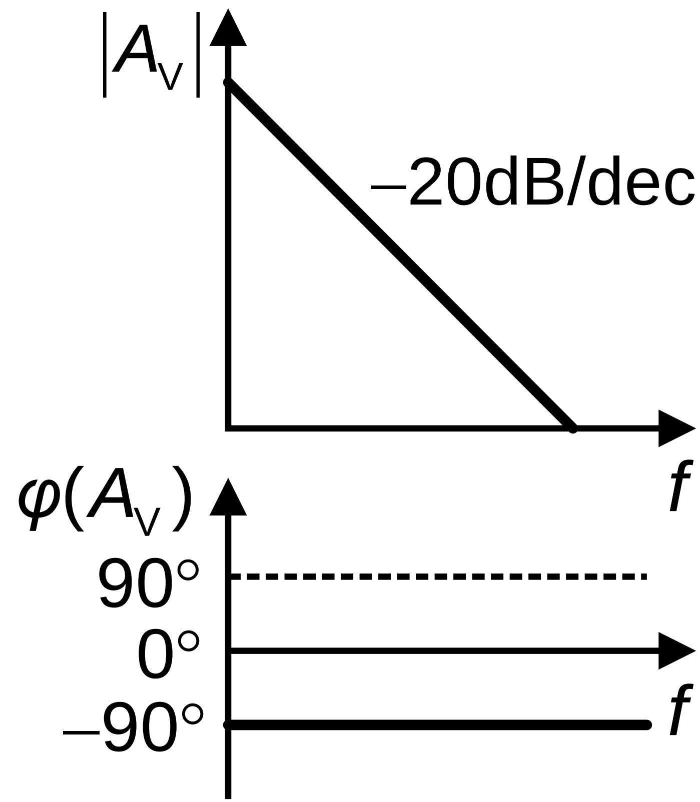
$$R_{IN} = \infty$$

$$A_V = 1$$

$$R_{IN} = \infty$$

积分器

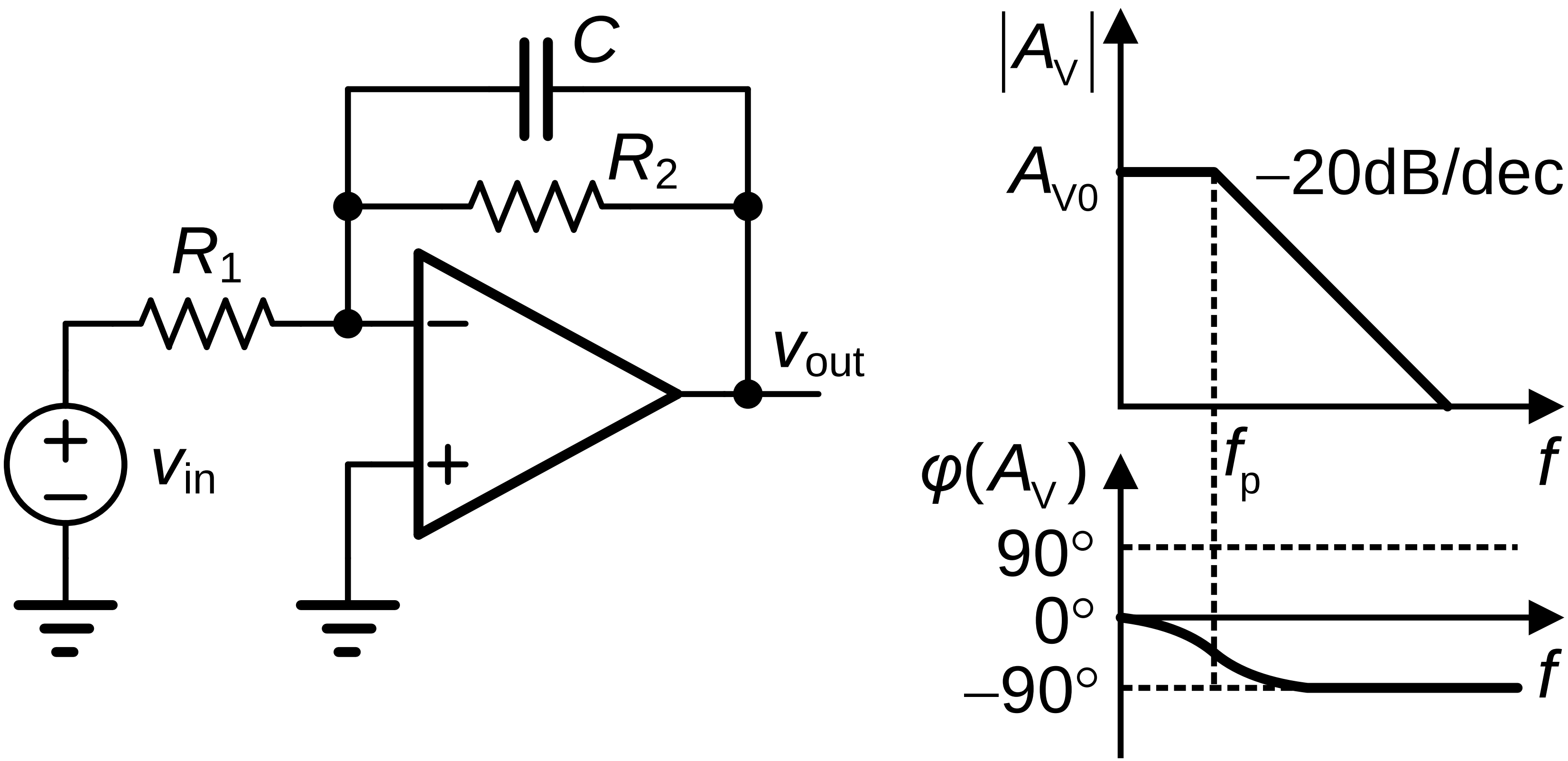




$$A_V = -\frac{1}{j\frac{f}{f_p}}$$

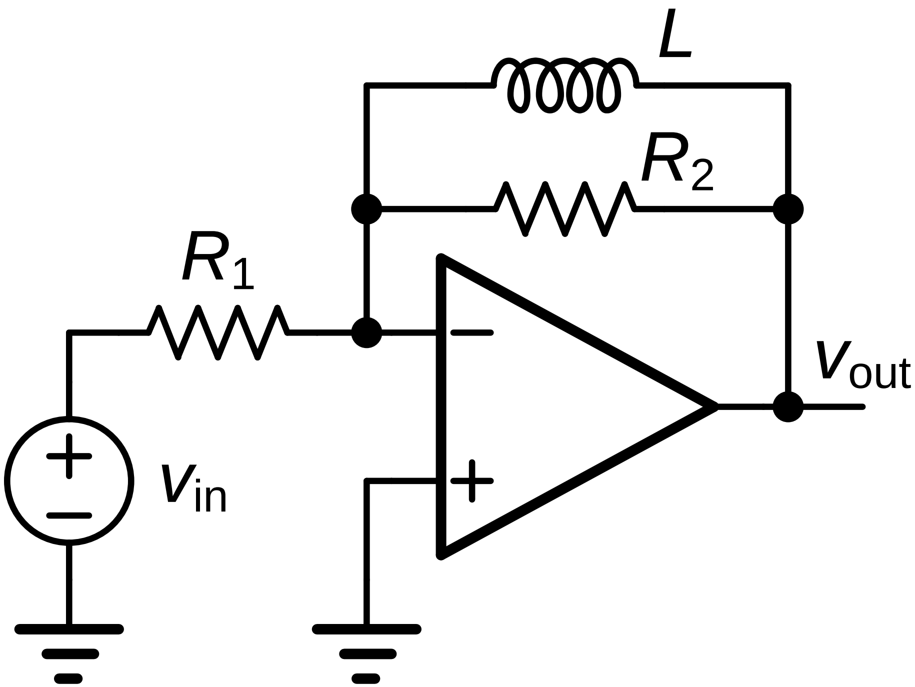
$$f_p = \frac{1}{2\pi RC}$$

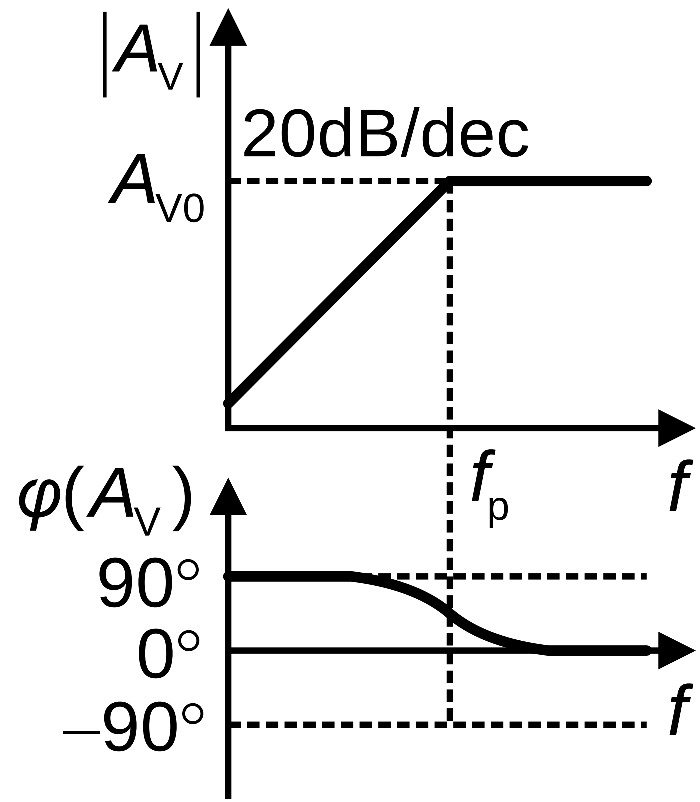
有损积分器：低通滤波器



$$A_{V0} = -\frac{R_2}{R_1} \qquad A_V = A_{V0}\frac{1}{1+\mathrm{j}\frac{f}{f_p}} \qquad f_p = \frac{1}{2\pi R_2 C}$$

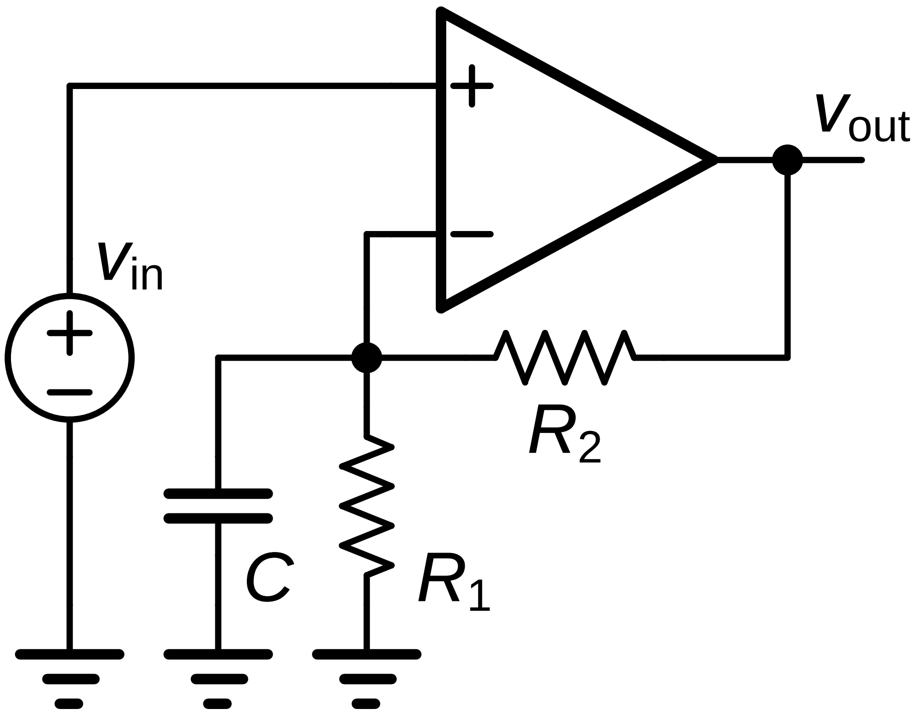
高通滤波器 1

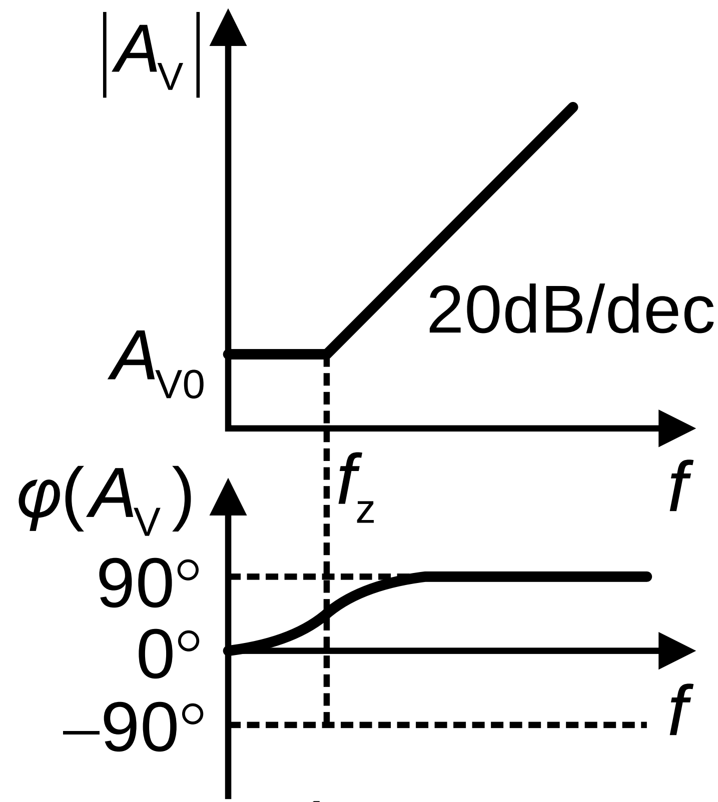




$$A_{V0} = -\frac{R_2}{R_1} \qquad A_V = A_{V0}\frac{\mathrm{j}\frac{f}{f_p}}{1+\mathrm{j}\frac{f}{f_p}} \qquad f_p = \frac{R_2}{2\pi L}$$

高通滤波器 2

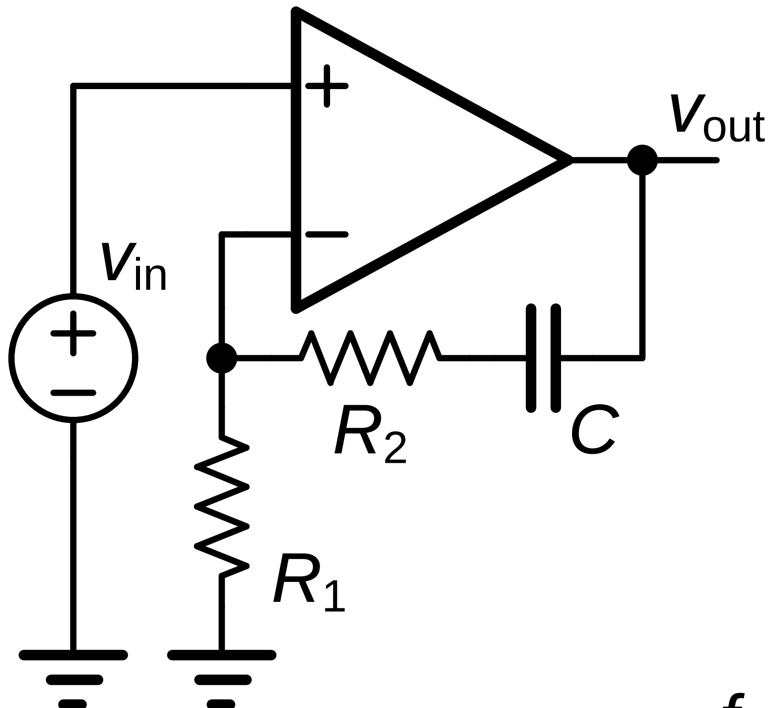


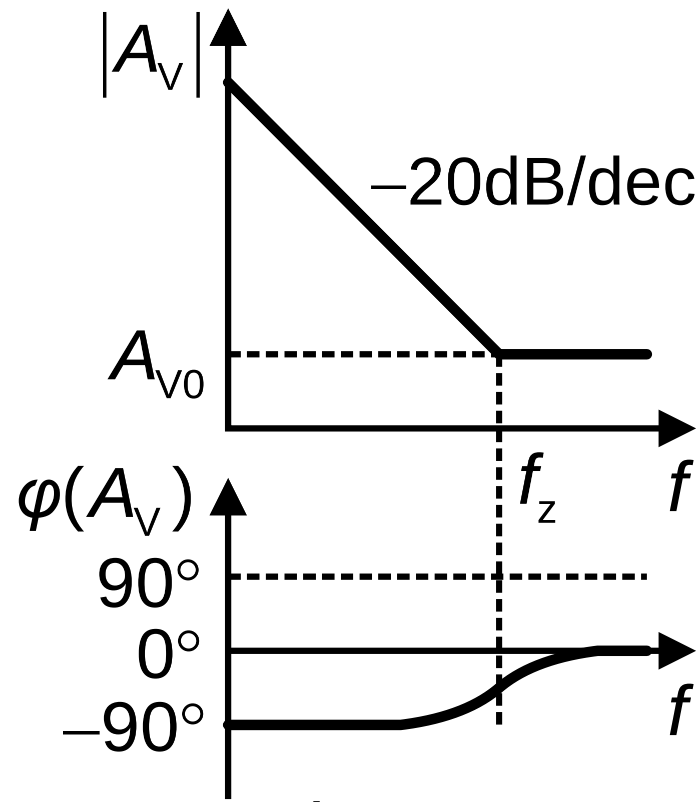


$$A_{V0} = 1 + \frac{R_2}{R_1} \qquad A_V = A_{V0}\left(1 + j\frac{f}{f_z}\right) \qquad f_z = \frac{1}{2\pi RC}$$

$$R = R_1 // R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

有限衰减的低通滤波器





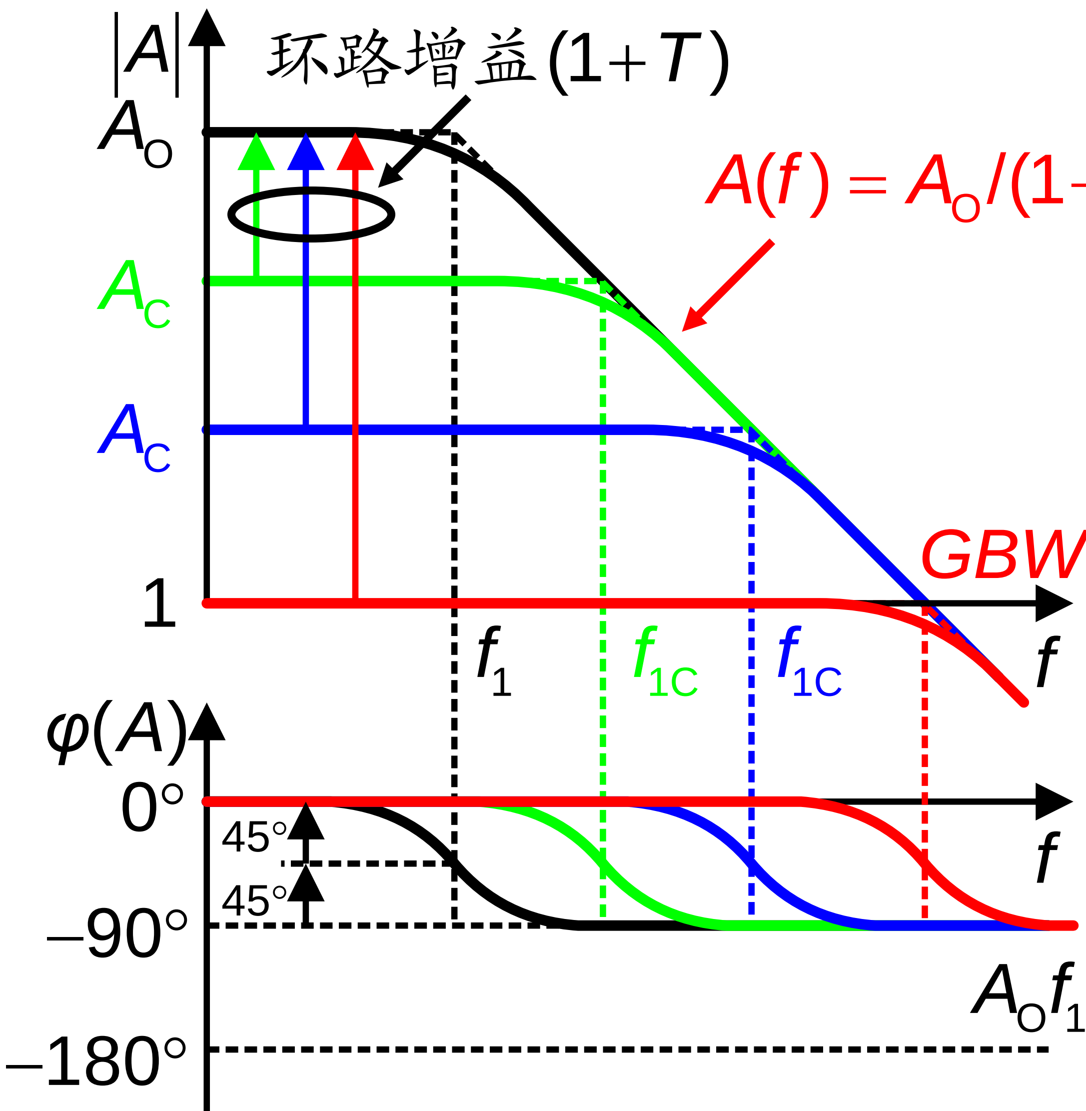
$$A_{V0} = 1 + \frac{R_2}{R_1}$$

$$A_V = A_{V0} \frac{1 + j\frac{f}{f_z}}{j\frac{f}{f_z}}$$

$$f_z = \frac{1}{2\pi RC}$$

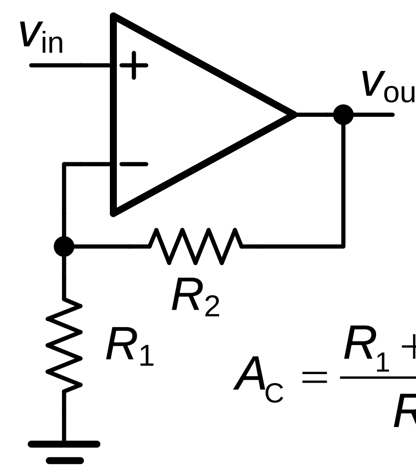
$$R = R_1 + R_2$$

增益和带宽之间的交换



A_O 开环增益

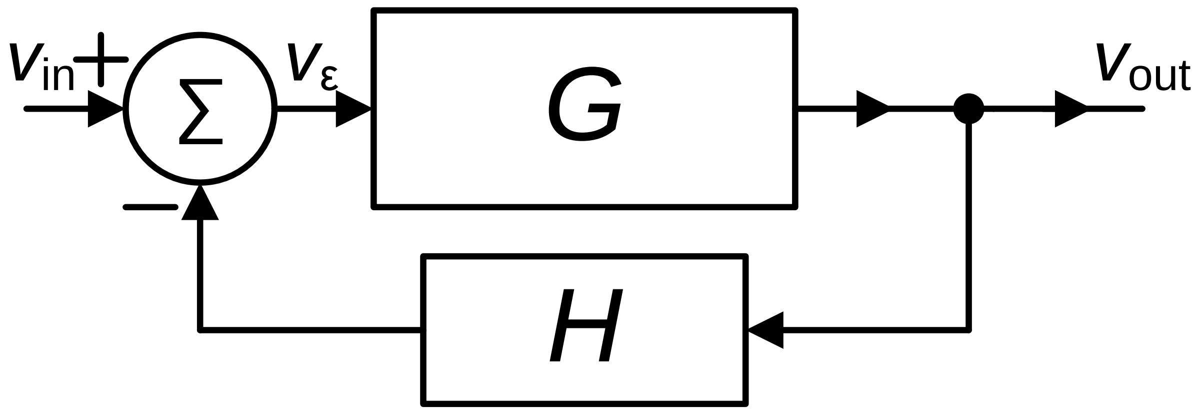
A_C 闭环增益



$$A_C = \frac{R_1 + R_2}{R_1}$$

$$A_O f_1 = A_C f_{1C} = A_C f_{1C} = GBW$$

开环增益和闭环增益

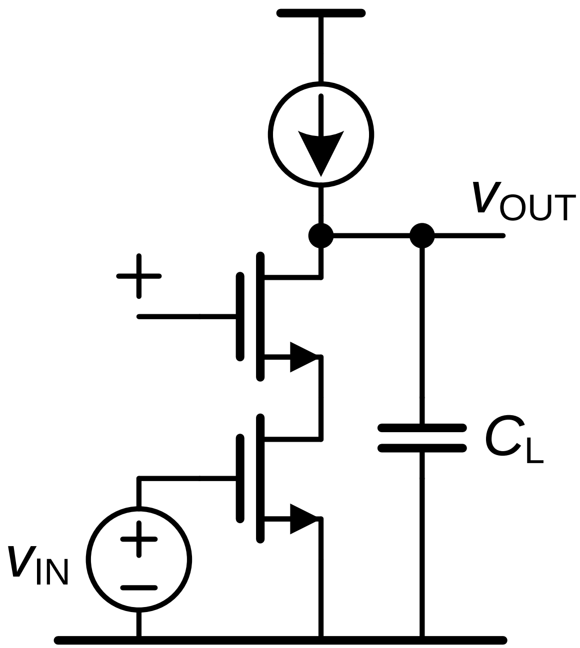


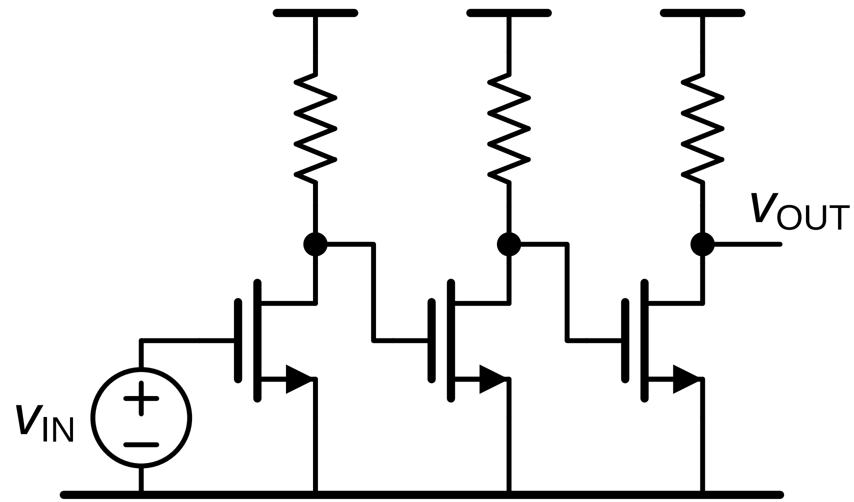
$$\left.\begin{aligned} v_\varepsilon &= v_{in} - H v_{out} \\ v_{out} &= G v_\varepsilon \end{aligned}\right\} \Rightarrow A_C = \frac{v_{out}}{v_{in}} = \frac{G}{1+GH} \approx \frac{1}{H}$$

如果环路增益 $GH = T \gg 1$

Ref.: P. Gray, P.Hurst, S.Lewis, R. Meyer: Design of analog integrated circuits, 4th ed., Wiley 2001

运放成为运放的原因？

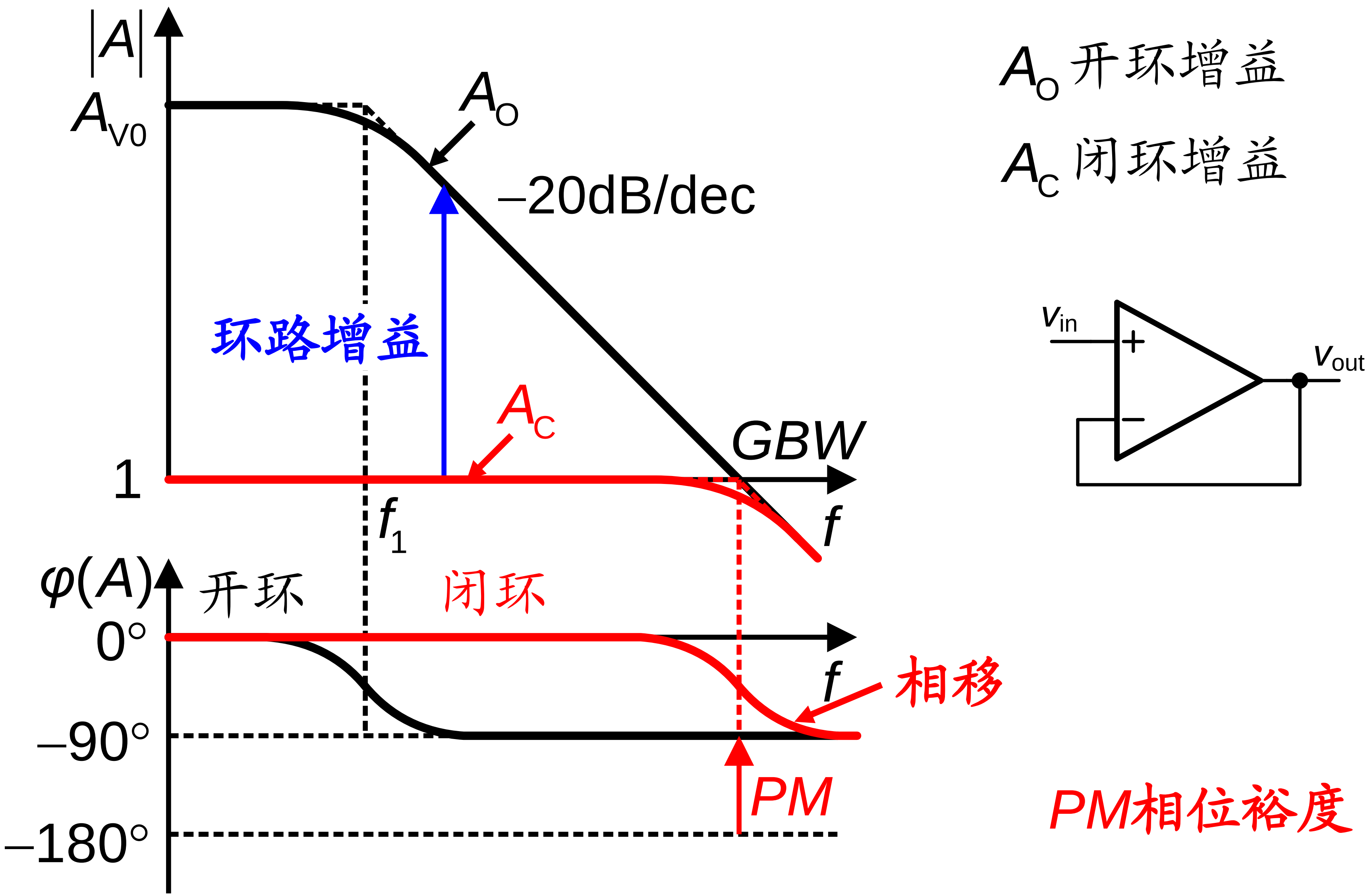




运算放大器
单级点放大器
高阻抗=高增益
增益与带宽交换
任何增益下都稳定

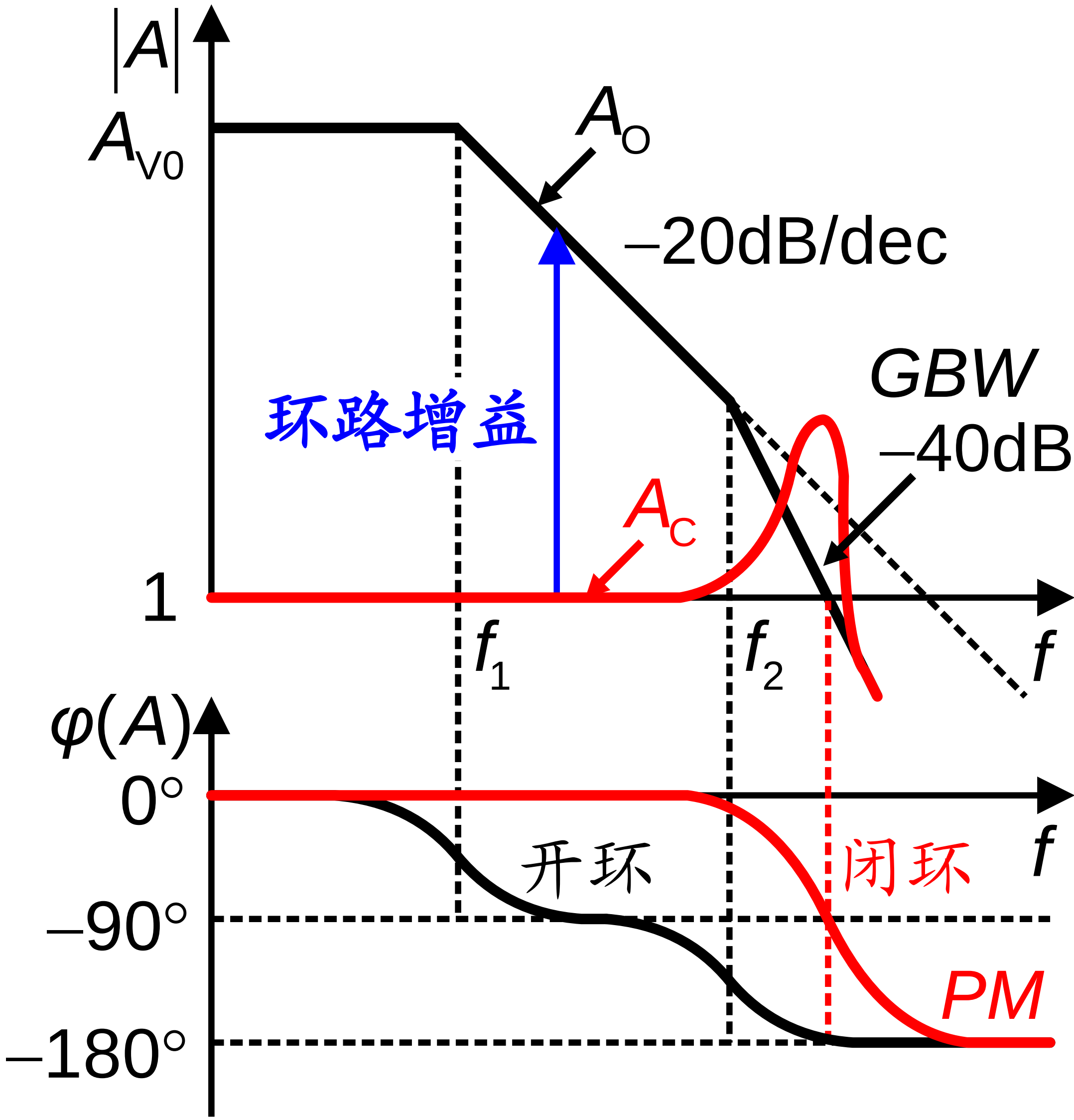
宽带放大器
多级点放大器
低阻抗节点
高带宽
只在某些增益下稳定

单极点系统



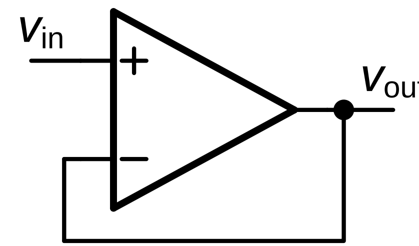
PM相位裕度

双极点系统



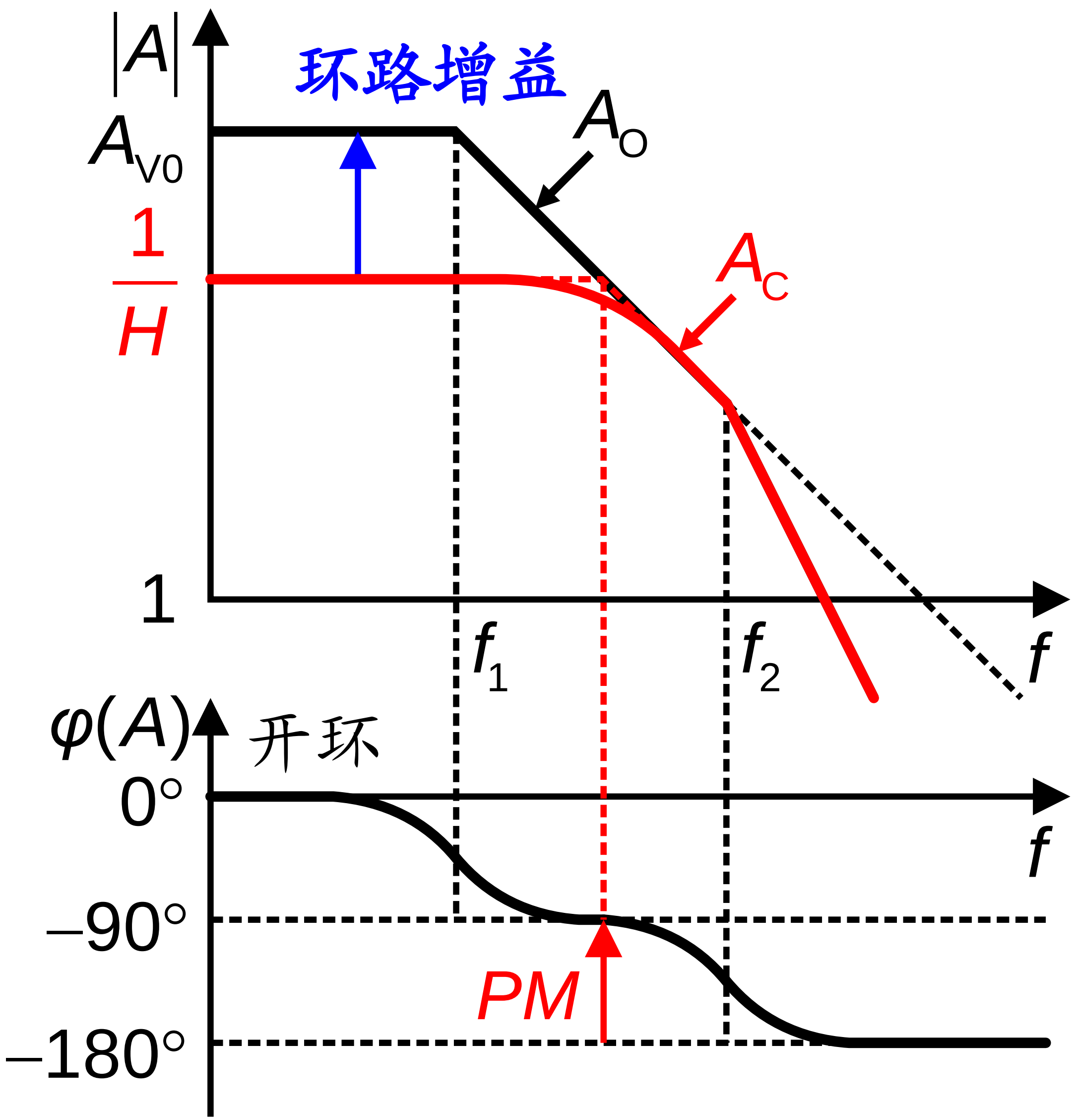
A_O 开环增益

A_C 闭环增益



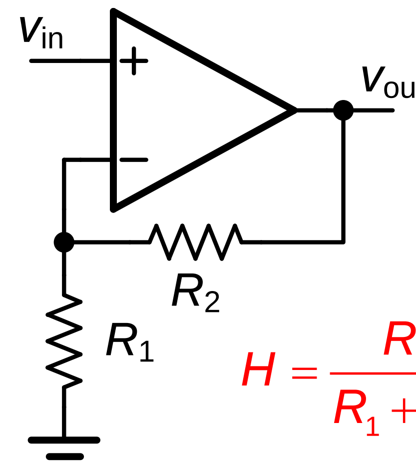
PM相位裕度

环路增益与相位裕度的关系 1



A_O 开环增益

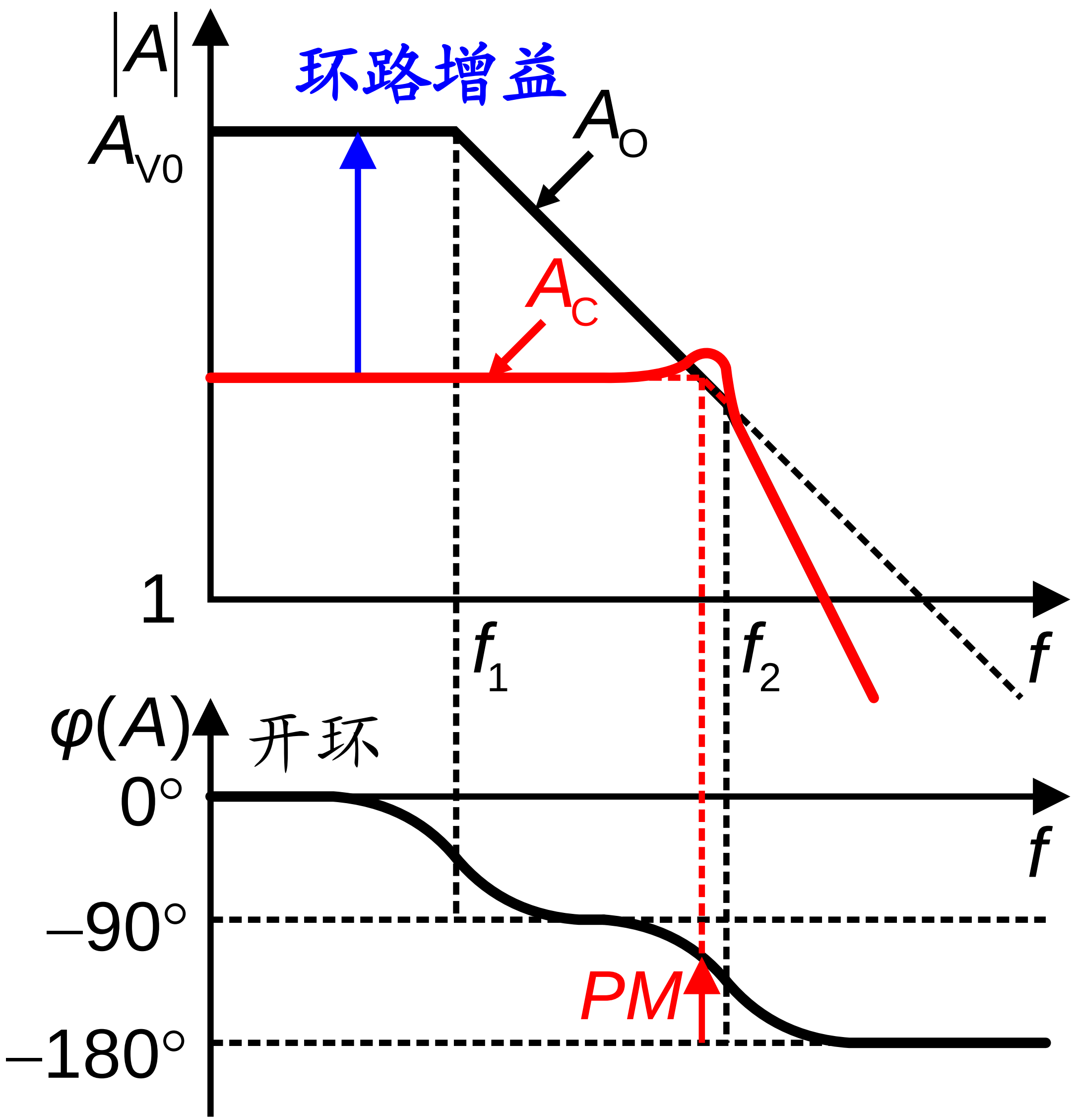
A_C 闭环增益



$$H = \frac{R_1}{R_1 + R_2}$$

PM相位裕度

环路增益与相位裕度的关系 2

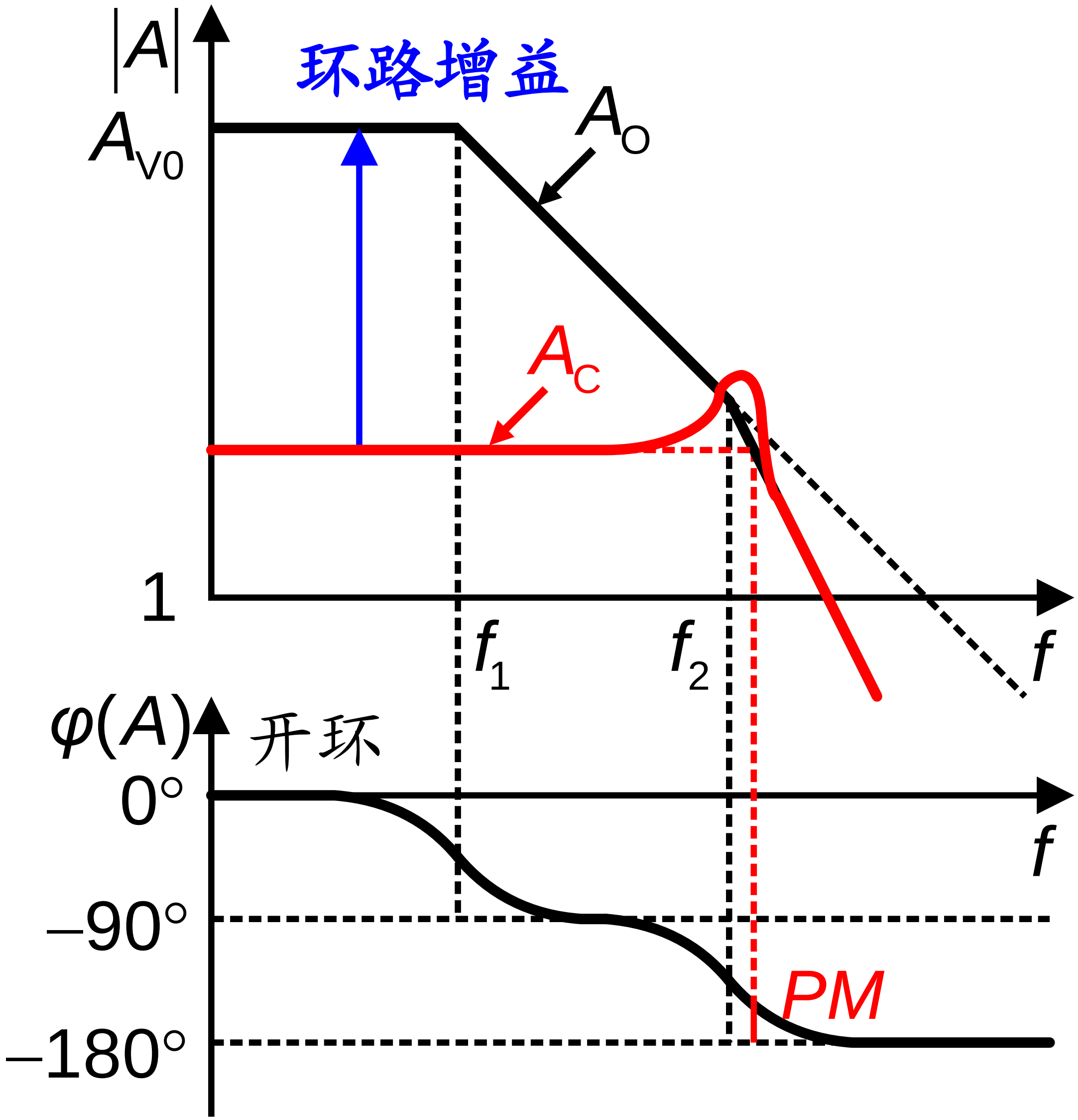


A_O 开环增益

A_C 闭环增益

PM相位裕度

环路增益与相位裕度的关系 3

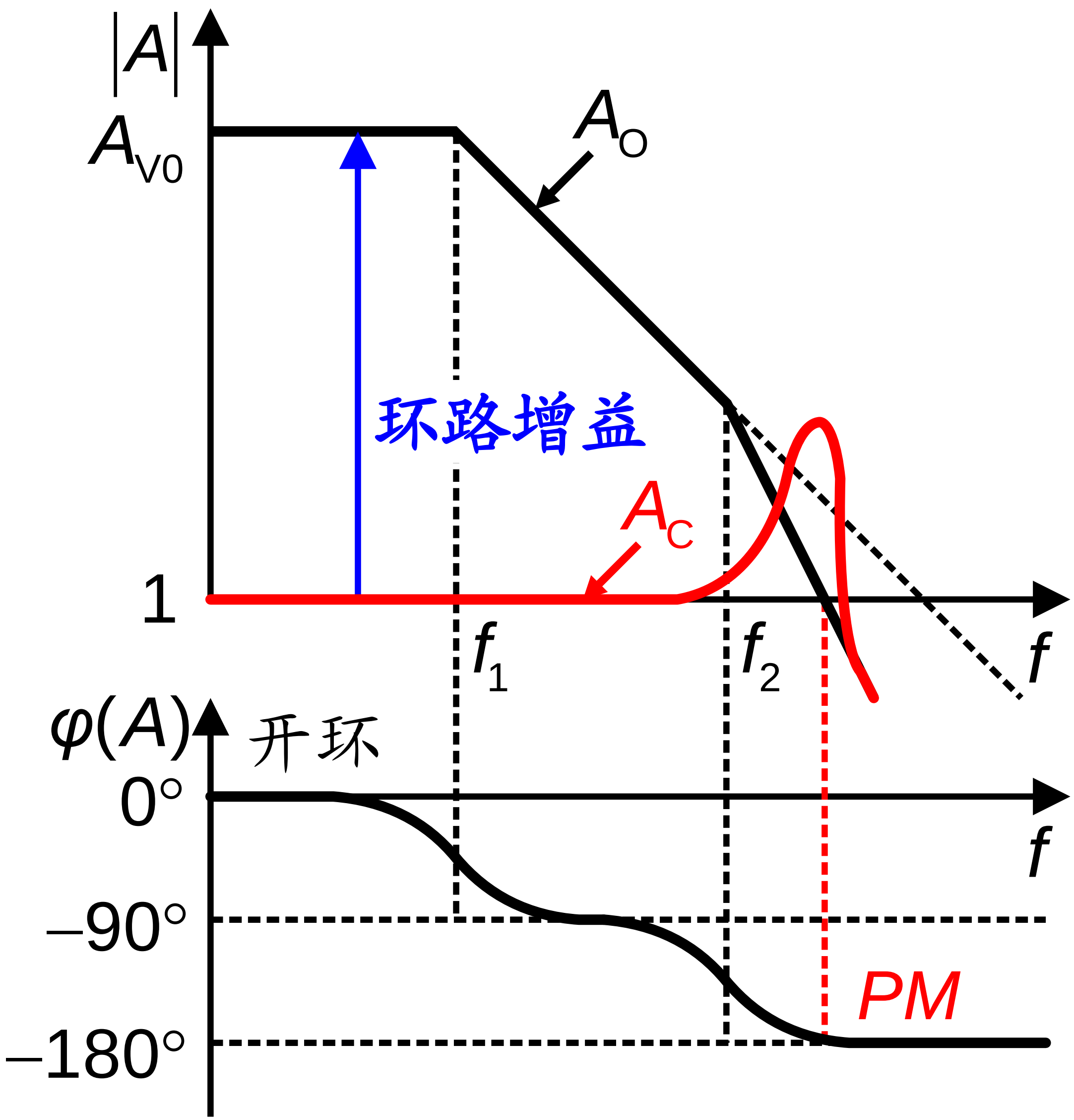


A_O 开环增益

A_C 闭环增益

PM相位裕度

环路增益与相位裕度的关系 4



A_O 开环增益

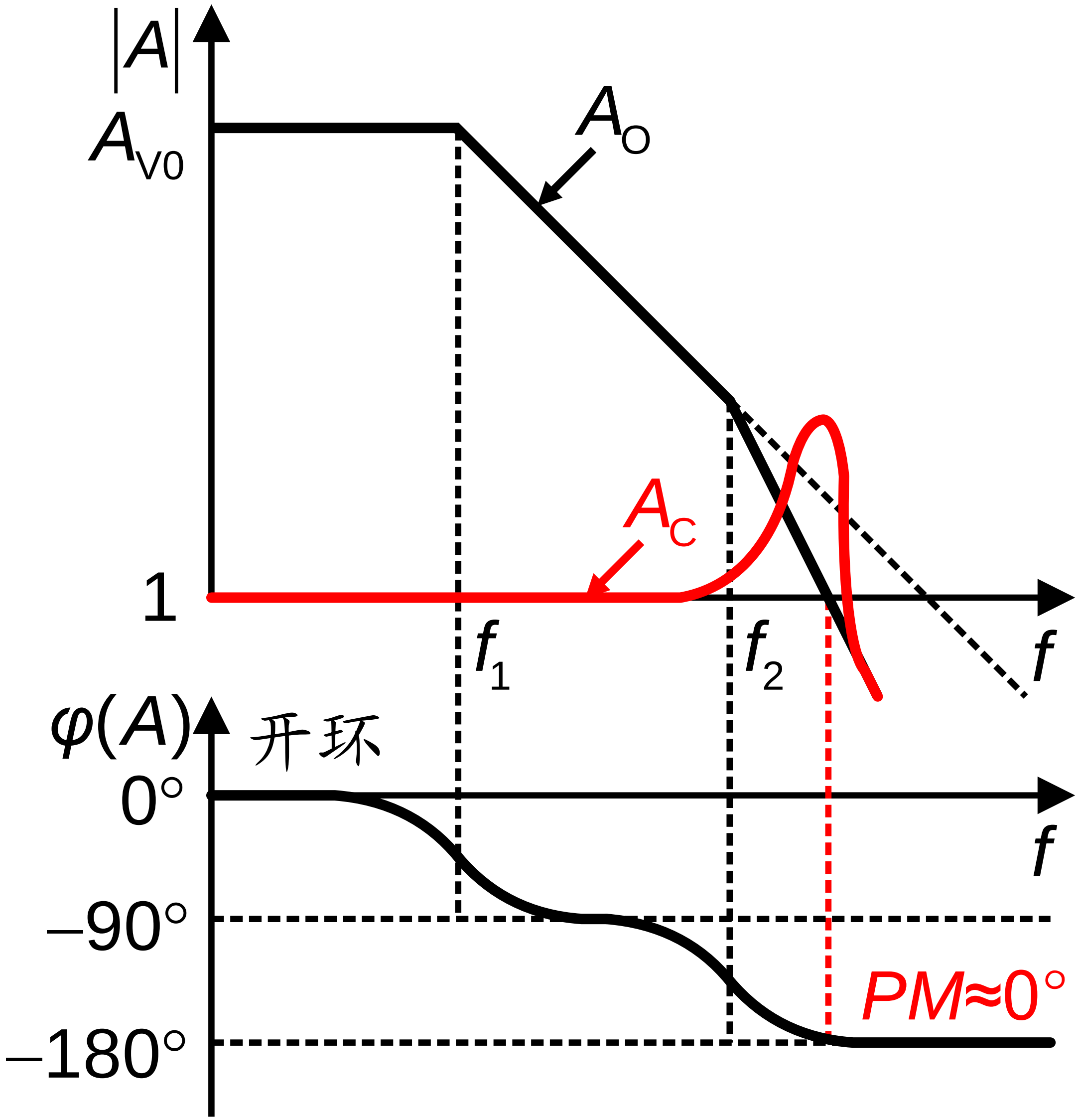
A_C 闭环增益

最坏情况

$A_C = 1$

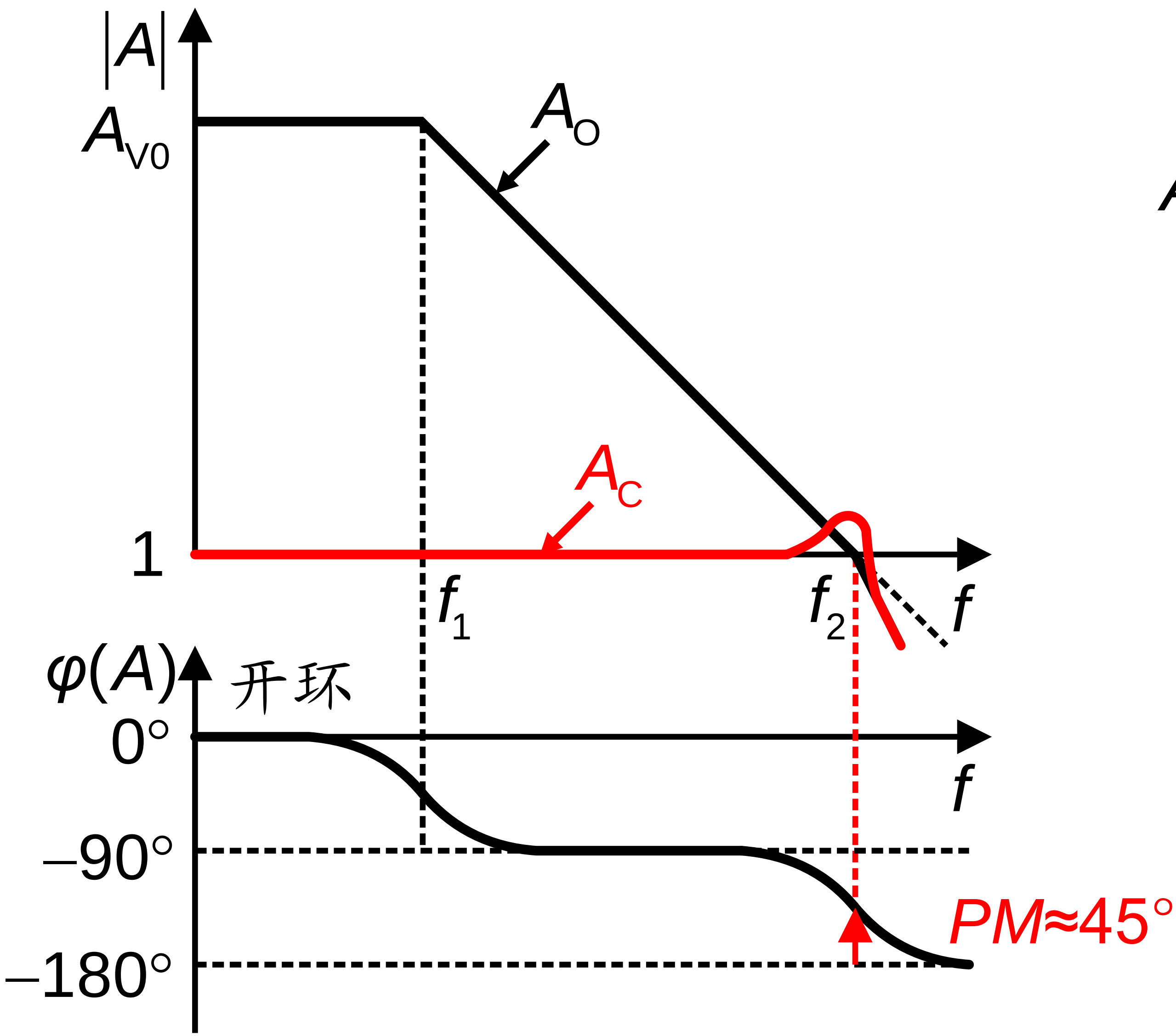
PM相位裕度

当f_2频率较低时



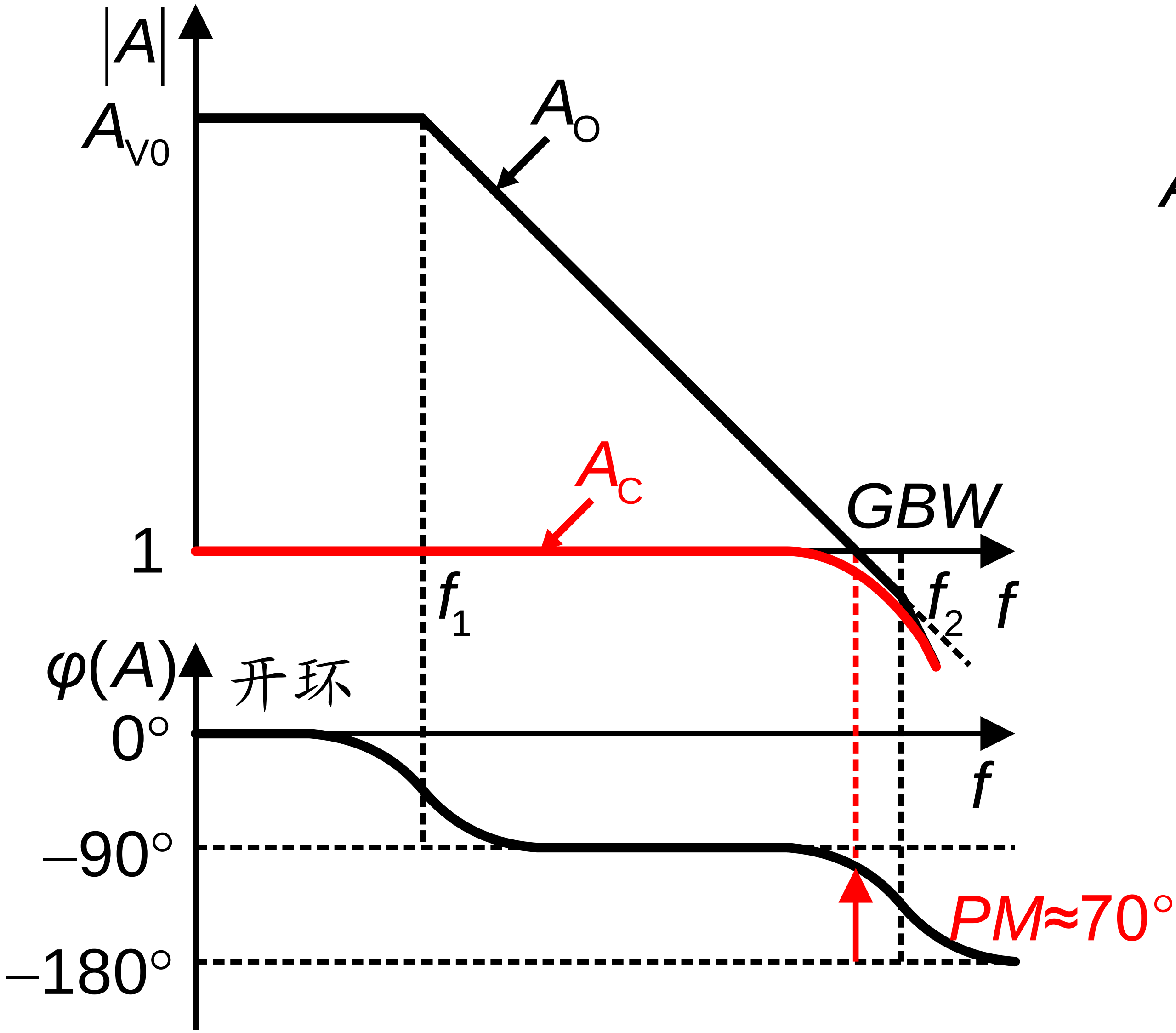
A_C 闭环增益

通过增加f_2，提高PM。(f_2=GBW)



A_C 闭环增益

通过增加f_2，提高PM。(f_2≈3GBW)

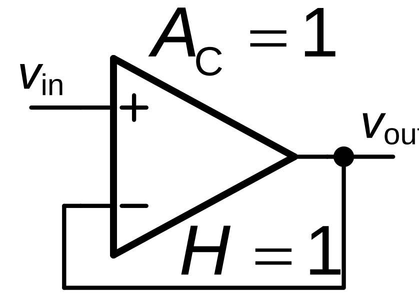


A_C 闭环增益

$f_2 \approx 3GBW$

当f_2≈3GBW时，计算PM

开环增益 $$A_O = \frac{A_{V0}}{(1+j\frac{f}{f_1})(1+j\frac{f}{f_2})}$$



闭环增益 $$A_C = \frac{A_O}{1+A_O} \approx \frac{A_{V0}}{1+A_{V0}} \frac{1}{1+j\frac{f}{GBW}+j^2\frac{f^2}{GBWf_2}}$$

$$\approx \frac{1}{1+j2\zeta\frac{f}{f_r}+j^2\frac{f^2}{f_r^2}}$$

$f_r = \sqrt{GBWf_2}$ 自激振荡频率

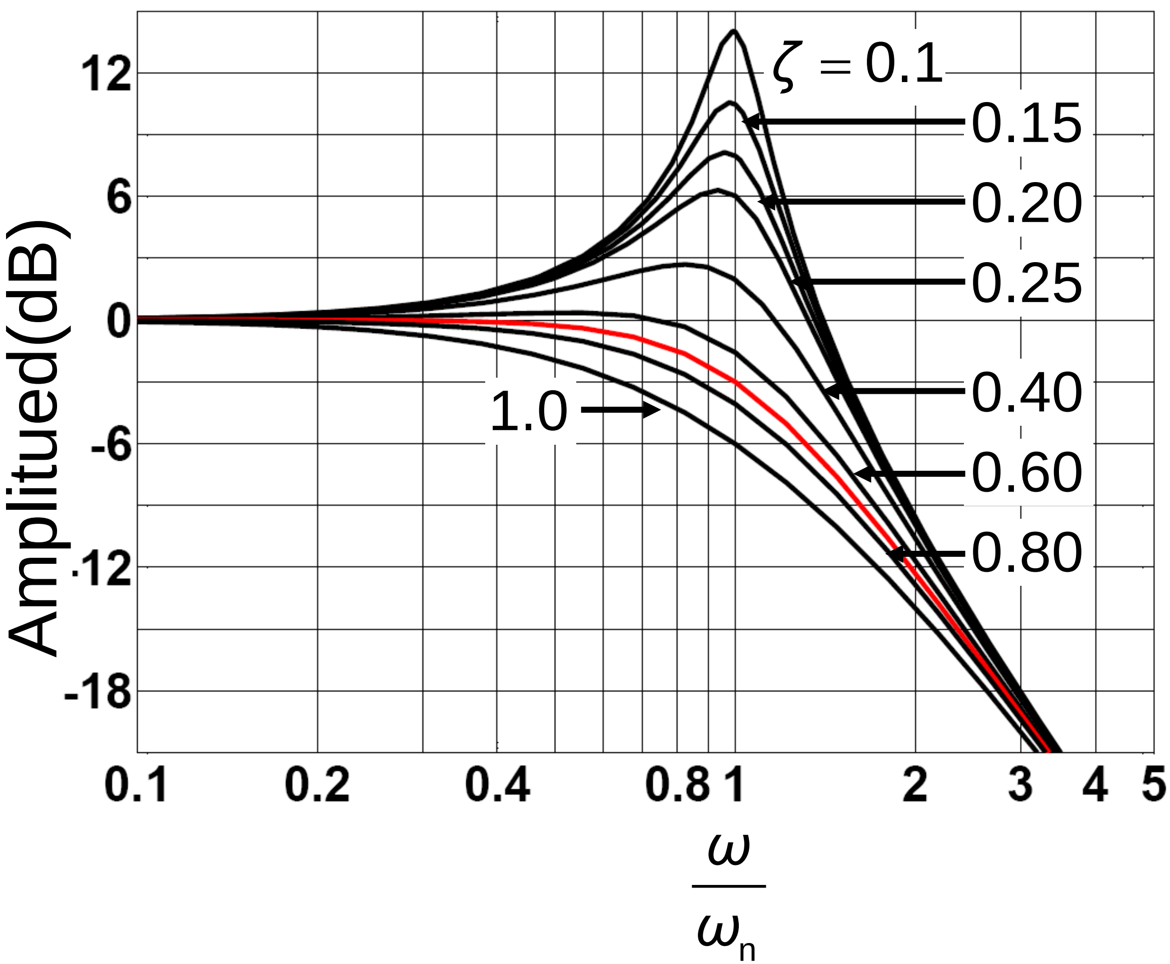
$\zeta = \frac{1}{2}\sqrt{\frac{f_2}{GBW}}$ 阻尼系数$(=1/2Q)$

PM, ζ, P_f和P_t

$$f_r = \sqrt{GBWf_2} \qquad PM(^\circ) = 90^\circ - \arctan\frac{GBW}{f_2} = \arctan\frac{f_2}{GBW}$$

$\frac{f_2}{GBW}$	$PM(^\circ)$	$\zeta = \frac{1}{2}\sqrt{\frac{f_2}{GBW}}$	$P_f(\text{dB})$	$P_t(\text{dB})$
0.5	27	0.35	3.6	2.3
1	45	0.5	1.25	1.3
1.5	56	0.61	0.28	0.73
2	63	$\sqrt{2}/2$	0	0.37
3	72	0.87	0	0.04
4	76	1		
5	79			

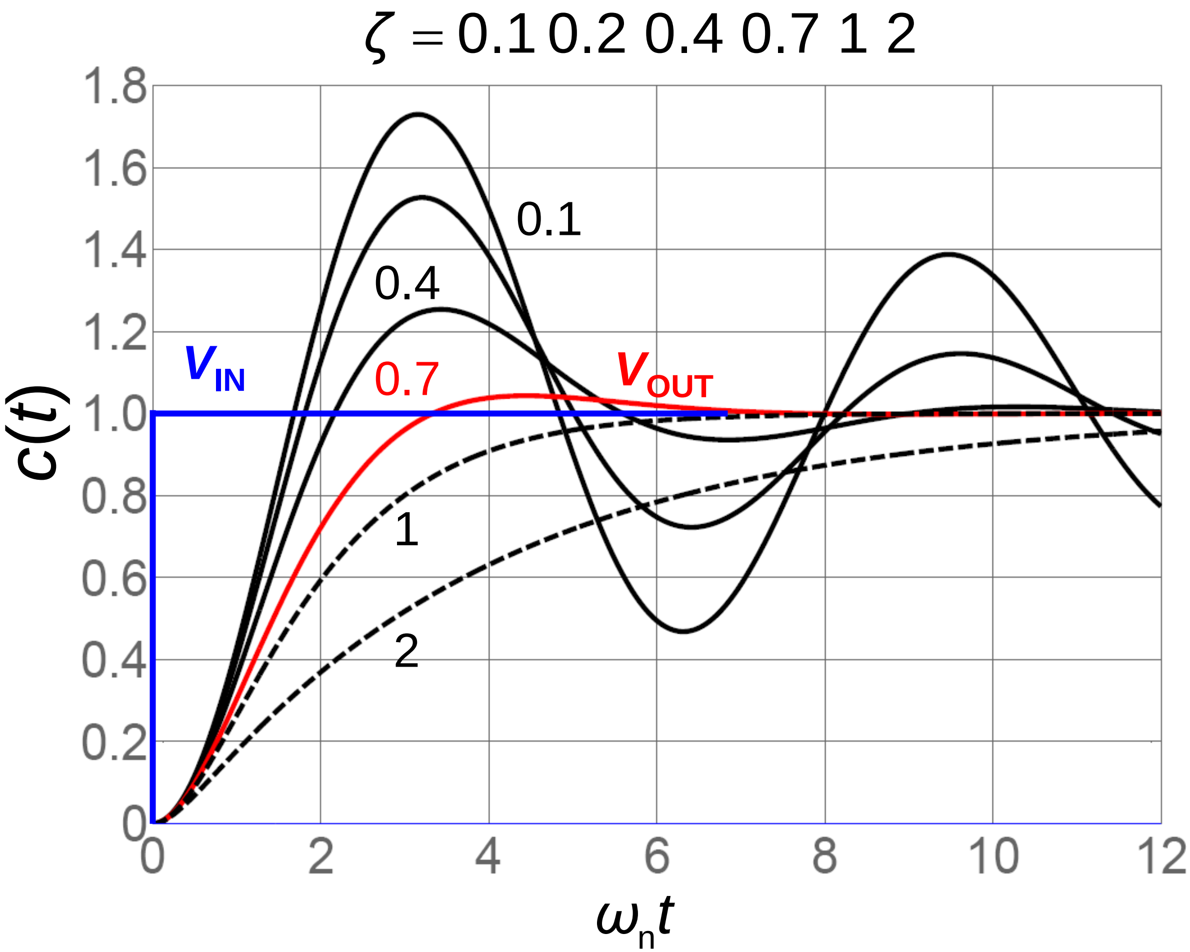
闭环幅度频率响应



$\zeta = Q = \sqrt{2}/2$

$$P_f = \frac{1}{2\zeta\sqrt{1-\zeta^2}}$$

闭环阶跃冲击响应



$$\zeta = Q = \sqrt{2}/2$$

$$P_t = 1 + e^{\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}}$$

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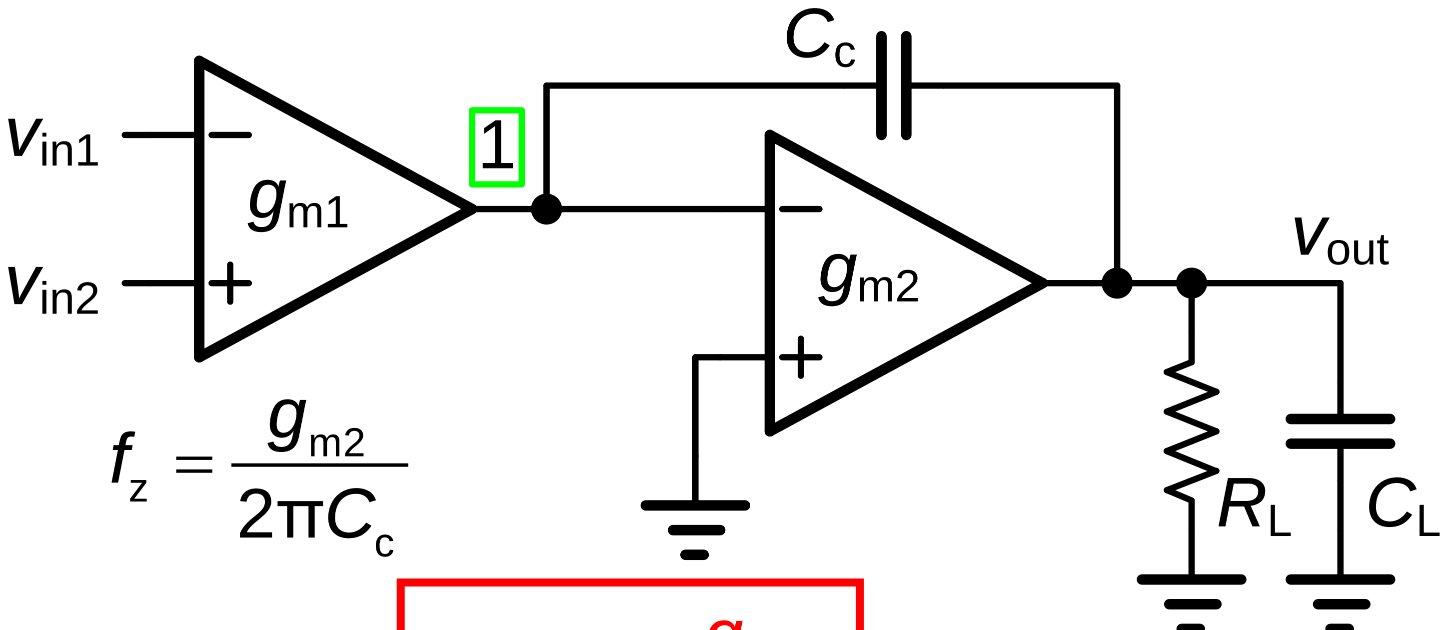
通用两级放大器 1

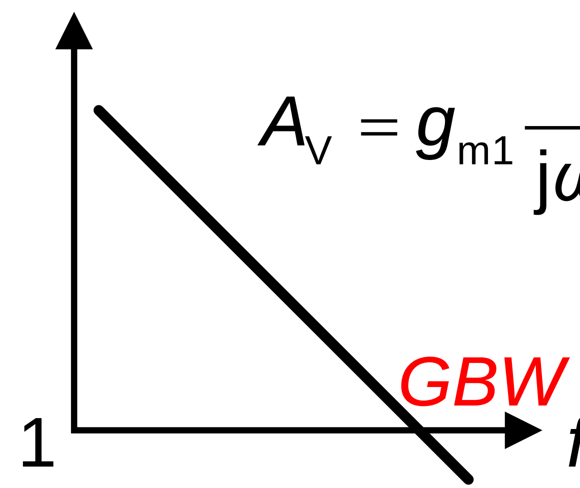


$$f_z = \frac{g_{m2}}{2\pi C_c}$$

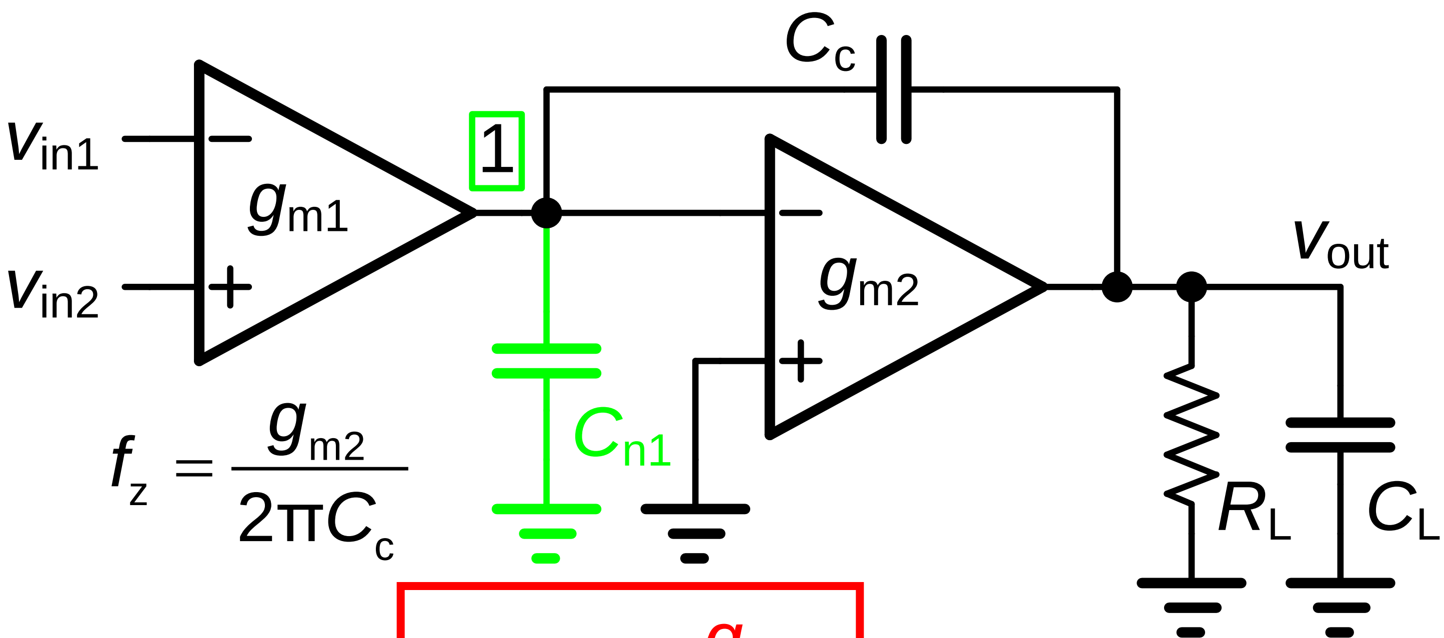
$$|A_V| = 1 \Rightarrow GBW = \frac{g_{m1}}{2\pi C_c}$$

$$f_{nd} = \frac{g_{m2}}{2\pi C_L}$$

$$A_V = g_{m1}\frac{1}{j\omega C_c}$$



通用两级放大器 2

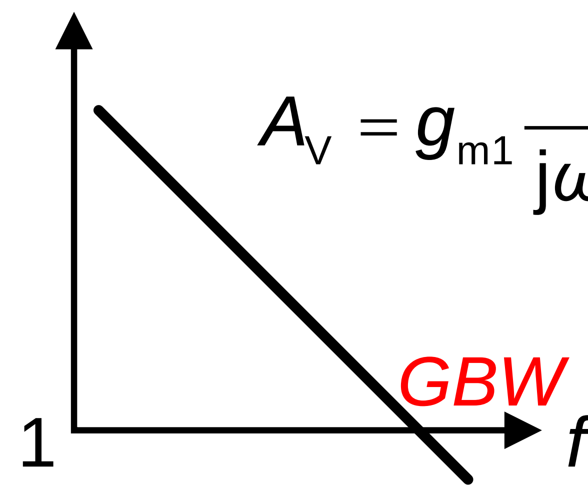


$$f_z = \frac{g_{m2}}{2\pi C_c}$$

$$|A_V| = 1 \Rightarrow GBW = \frac{g_{m1}}{2\pi C_c}$$

$$f_{nd} = \frac{g_{m2}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$$

$$A_V = g_{m1} \frac{1}{j\omega C_c}$$



初步设计两级运放

$$GBW = \frac{g_{m1}}{2\pi C_c} \qquad f_{nd} = \frac{g_{m2}}{2\pi C_L} \frac{1}{1+\underbrace{\frac{C_{n1}}{C_c}}_{\approx 0.3}}$$

$$\left.\begin{aligned} f_{nd} &= 3GBW \\ \frac{C_{n1}}{C_c} &\approx 0.3 \end{aligned}\right\} \Rightarrow \boxed{\frac{g_{m2}}{g_{m1}} \approx 4\frac{C_L}{C_c}}$$

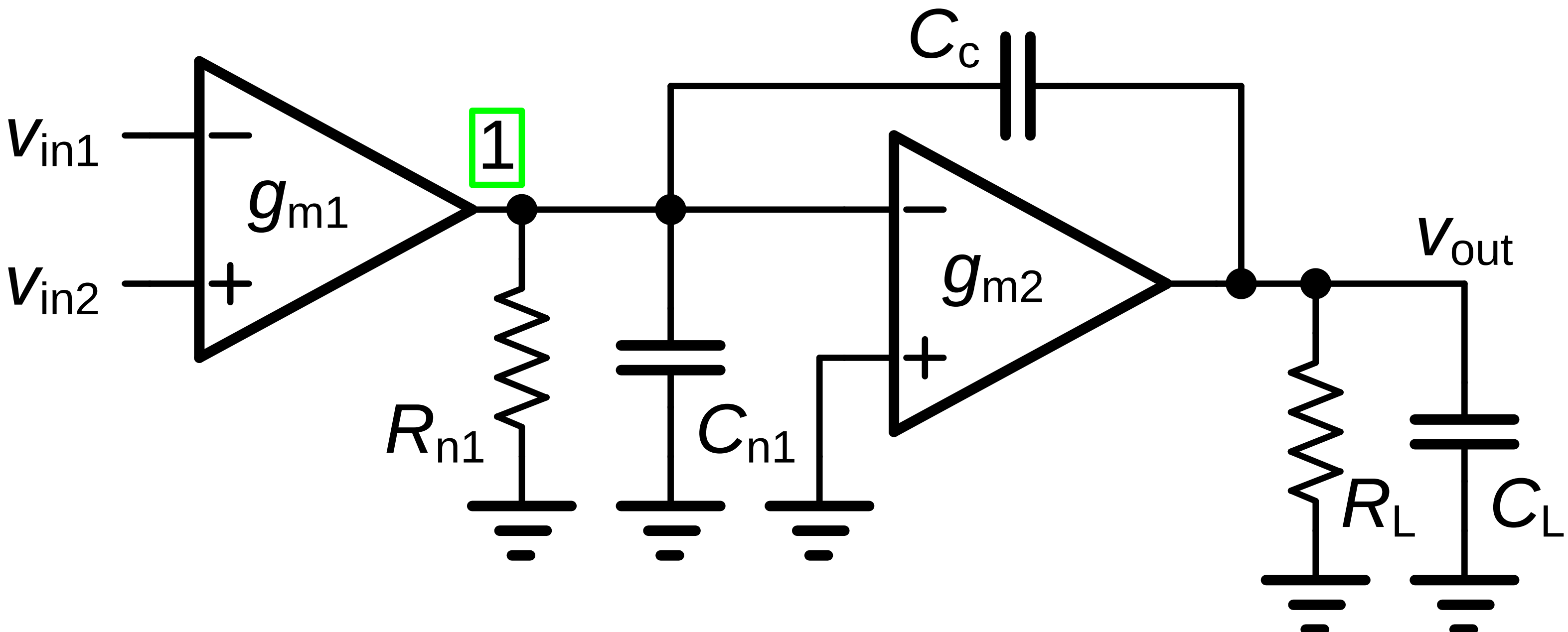
第二级需要很大的电流！

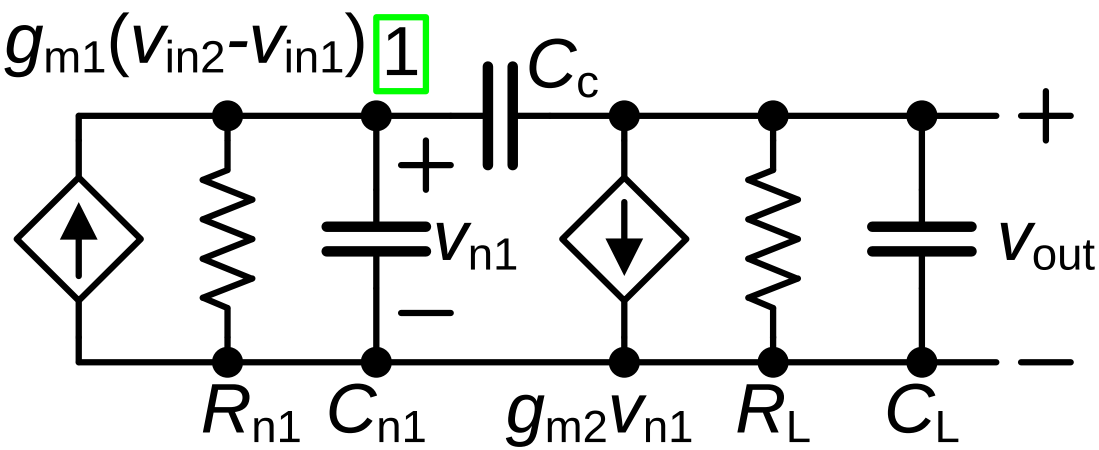
当 $GBW = 100\ \text{MHz}$、$C_L = 2\ \text{pF}$ 时

解： 选择 $C_c = 1\text{pF}$

目录

通用两级运放：密勒OTA



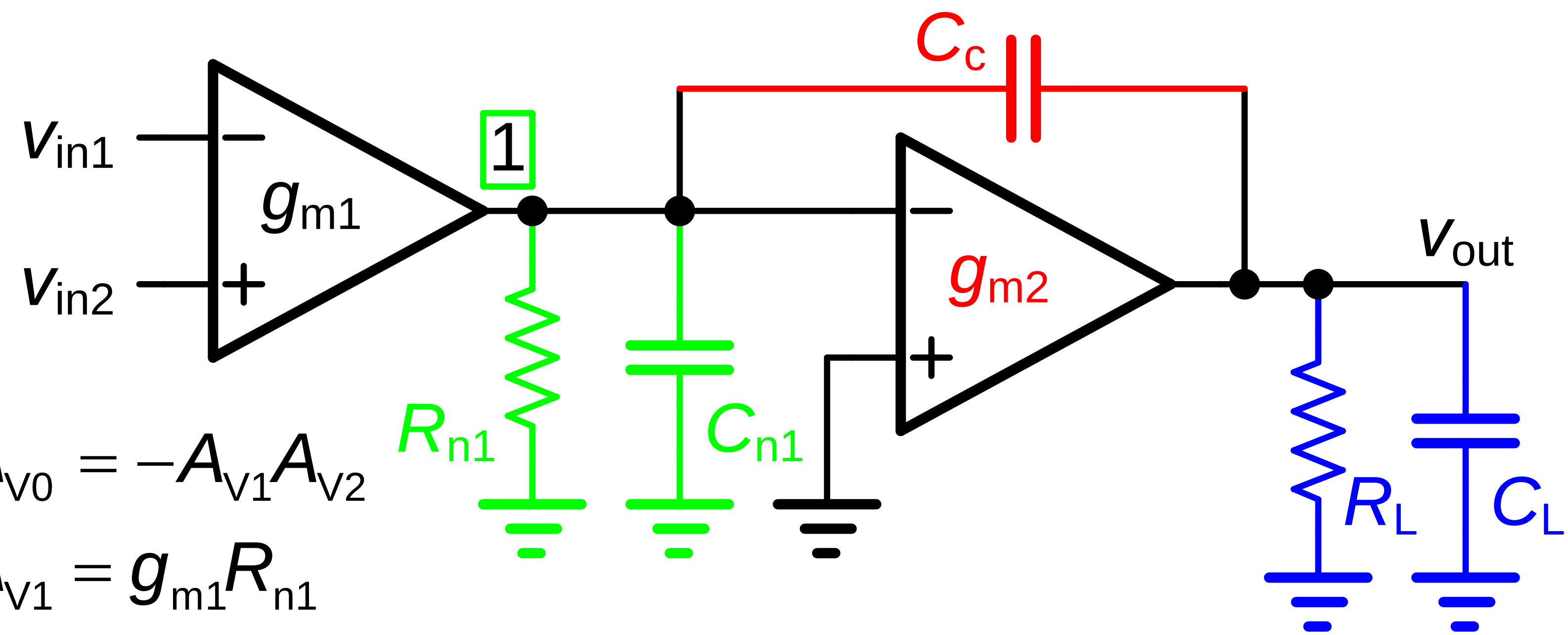


$$A_{V0} = -A_{V1}A_{V2}$$

$$A_{V1} = g_{m1}R_{n1}$$

$$A_{V2} = g_{m2}R_L$$

通用两级运放



$$A_{V0} = -A_{V1}A_{V2}$$

$$A_{V1} = g_{m1}R_{n1}$$

$$A_{V2} = g_{m2}R_L$$

$$A_V = A_{V0}\frac{1-\dfrac{C_c}{g_{m2}}s}{1+(R_{n1}C_{n1}+R_{n1}C_c+A_{V2}R_{n1}C_c+R_LC_L+R_LC_c)s+R_{n1}R_LCCs^2}$$

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

零极点近似

$$A = A_0 \frac{1 - cs}{1 + as + bs^2}$$

零点 $z = \frac{1}{c}$

极点 $s_1 = -\frac{1}{a} \quad s_2 = -\frac{a}{b}$

$a\uparrow \;\Rightarrow\; s_1\downarrow$ and $s_2\uparrow$

如果 $s_2 \gg s_1$ ：

s很小

$\Downarrow$

$1 + as + \cancel{bs^2} = 0$

$\Downarrow$

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

s很大

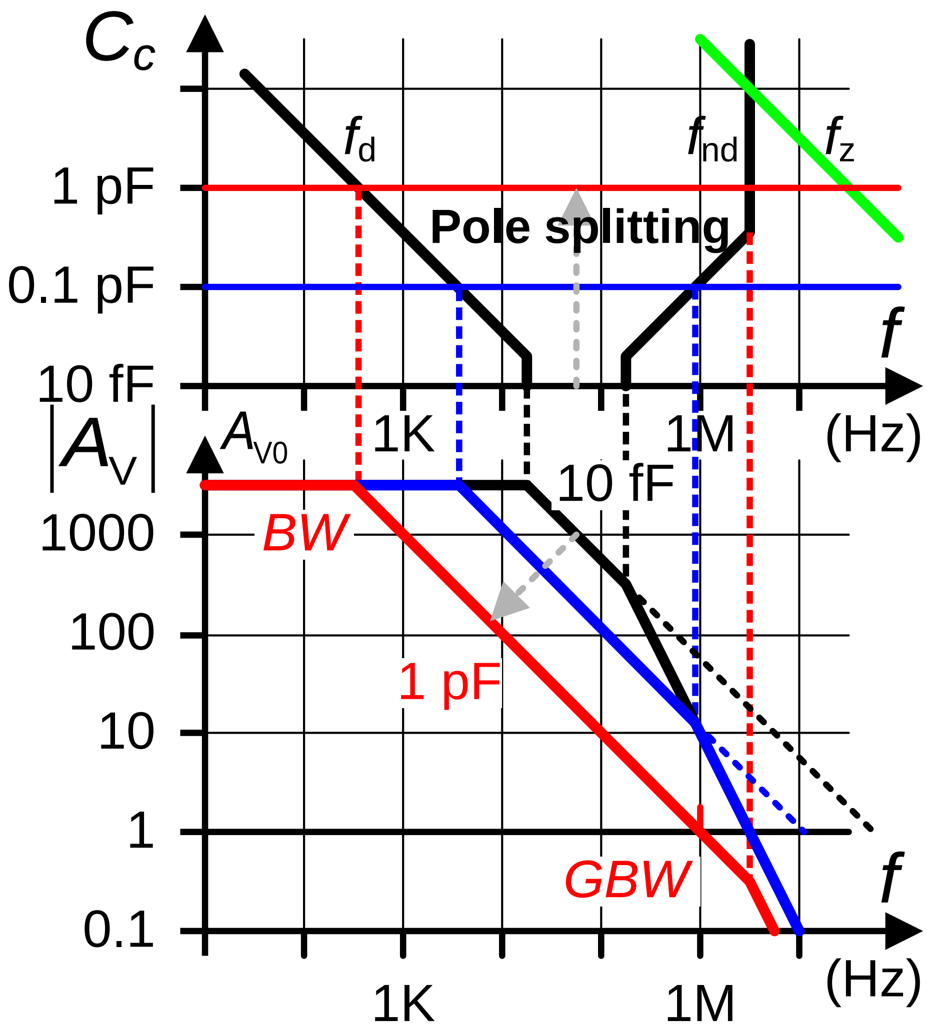
$\Downarrow$

$\cancel{1} + as + bs^2 = 0$

$\Downarrow$

$s_2 = -\frac{a}{b}$

密勒OTA：用C_c进行极点分离



C_c取较大值，

进行极点分离：

$$f_d = \frac{1}{2\pi A_{V2} R_{n1} C_c}$$

$$f_z = \frac{g_{m2}}{2\pi C_c}$$ 为正零点！

$$GBW = \frac{g_{m1}}{2\pi C_c}$$

正零点的作用

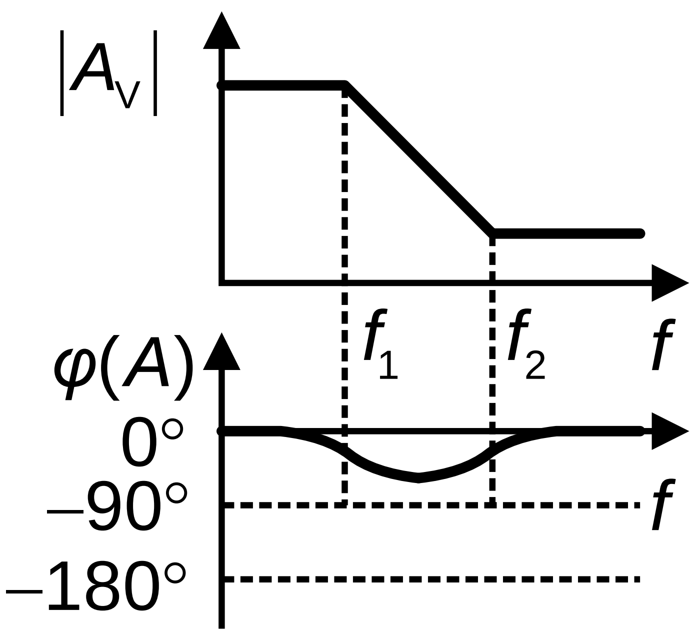
负零点

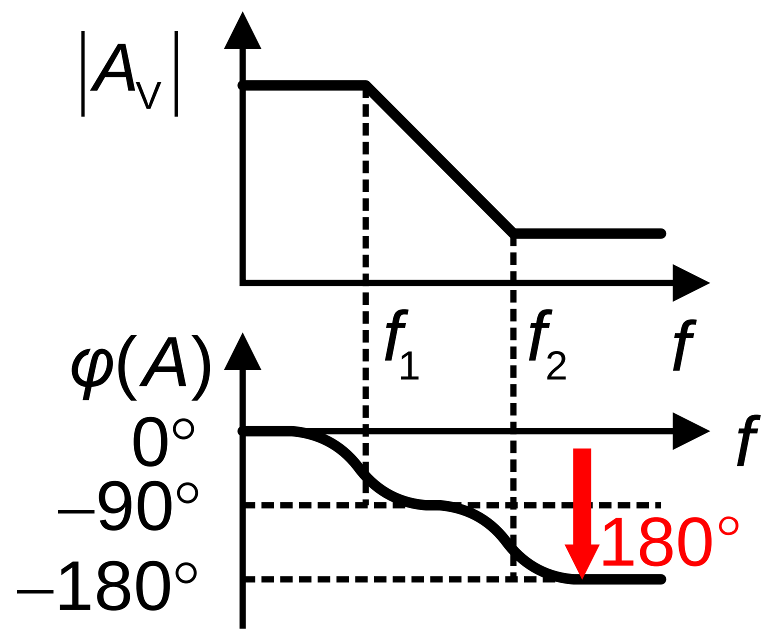
$$A_V = A_{V0}\frac{1+jf/f_2}{1+jf/f_1}$$

正零点

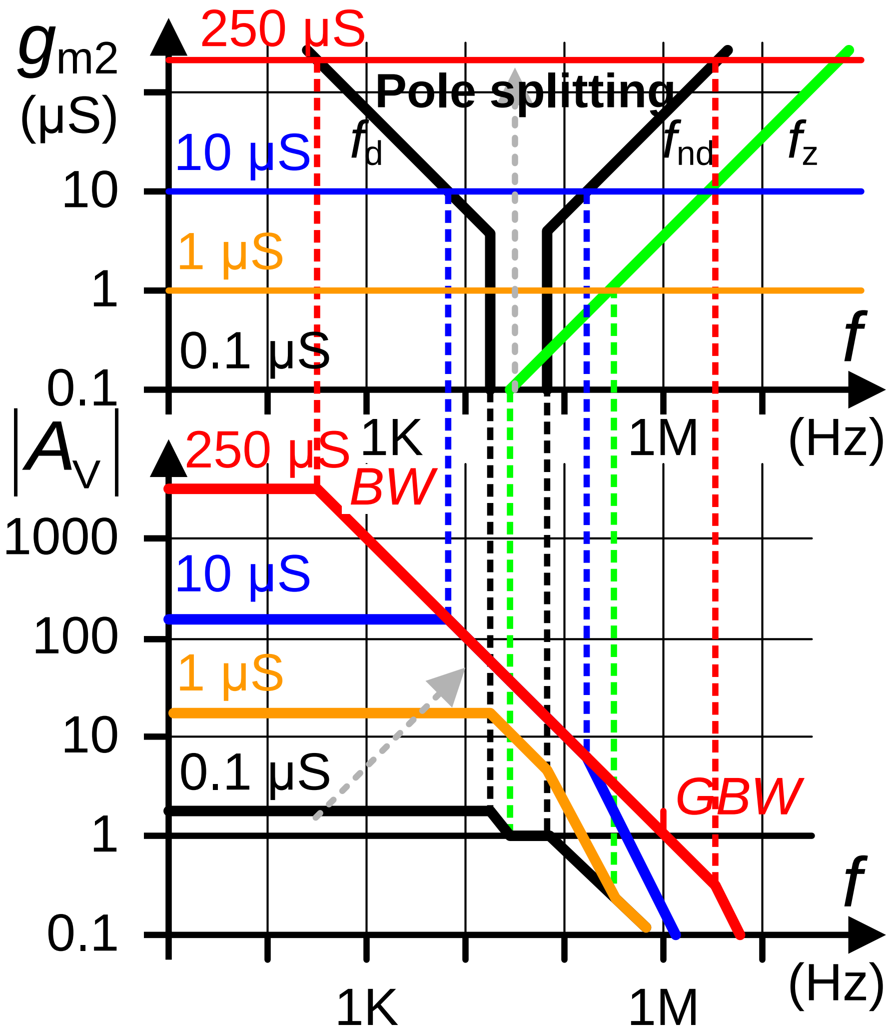
$$A_V = A_{V0}\frac{1-jf/f_2}{1+jf/f_1}$$

对于相位，正零点像一个负极点!!!





密勒OTA：用g_{m2}进行极点分离



g_{m2}取较大值，

进行极点分离：

$$f_d = \frac{1}{2\pi A_{V2} R_{n1} C_c}$$

$$f_z = \frac{g_{m2}}{2\pi C_c}$$ 为正零点！

$$GBW = \frac{g_{m1}}{2\pi C_c}$$

极点分离的方式

$$\frac{g_{m2}}{g_{m1}} \approx 4\frac{C_L}{C_c}$$ 或表示为 $$g_{m2}C_c \approx 4g_{m1}C_L$$

g_{m2} 和 C_c 二者均可

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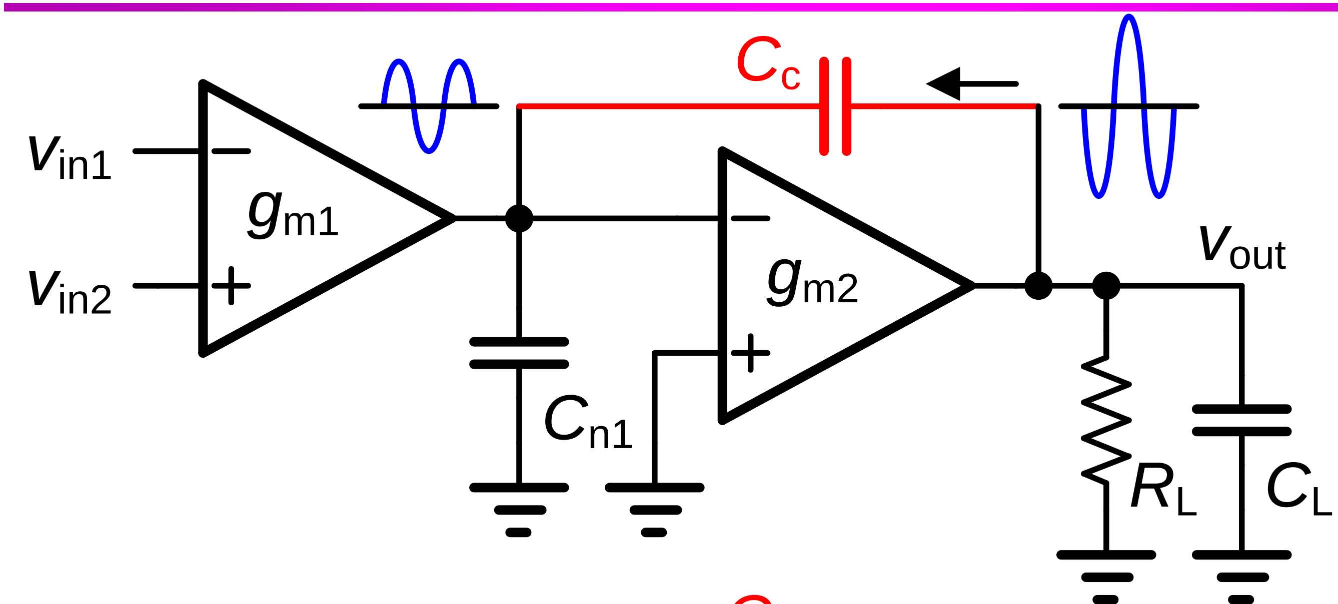
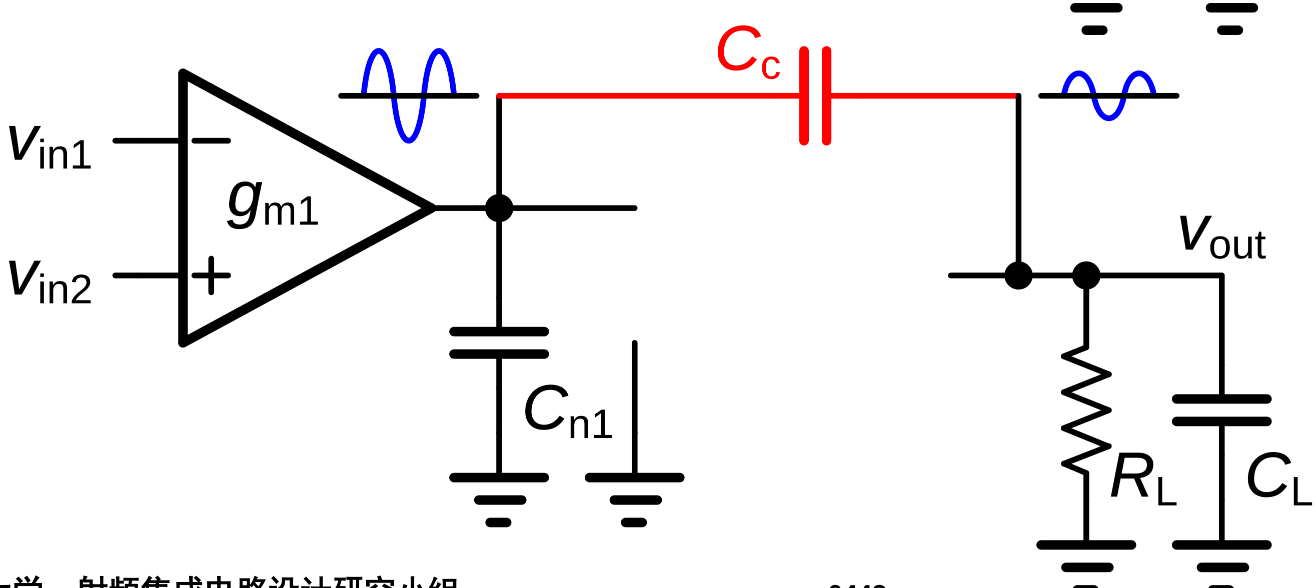
密勒效应的正反馈特性产生正零点



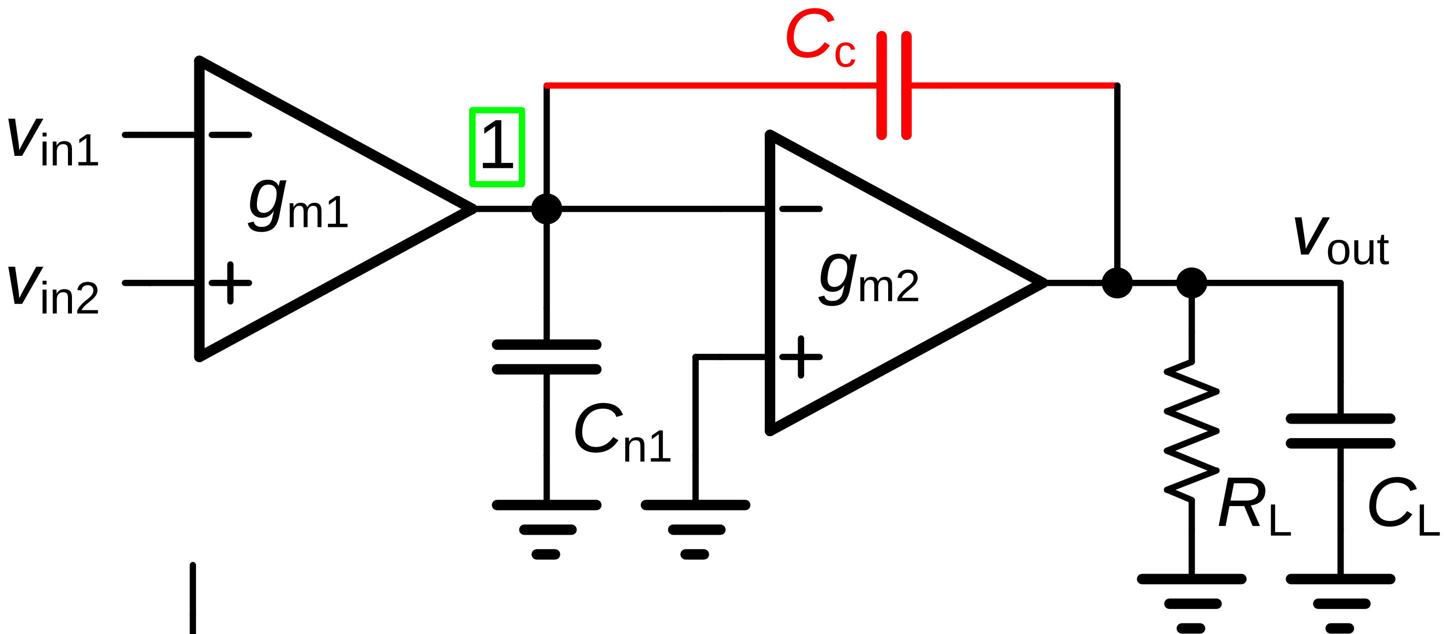
密勒效应为反馈

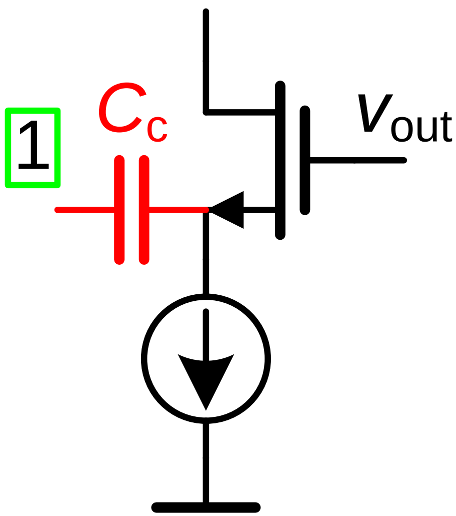


正馈

截断！

截断正馈通路 1

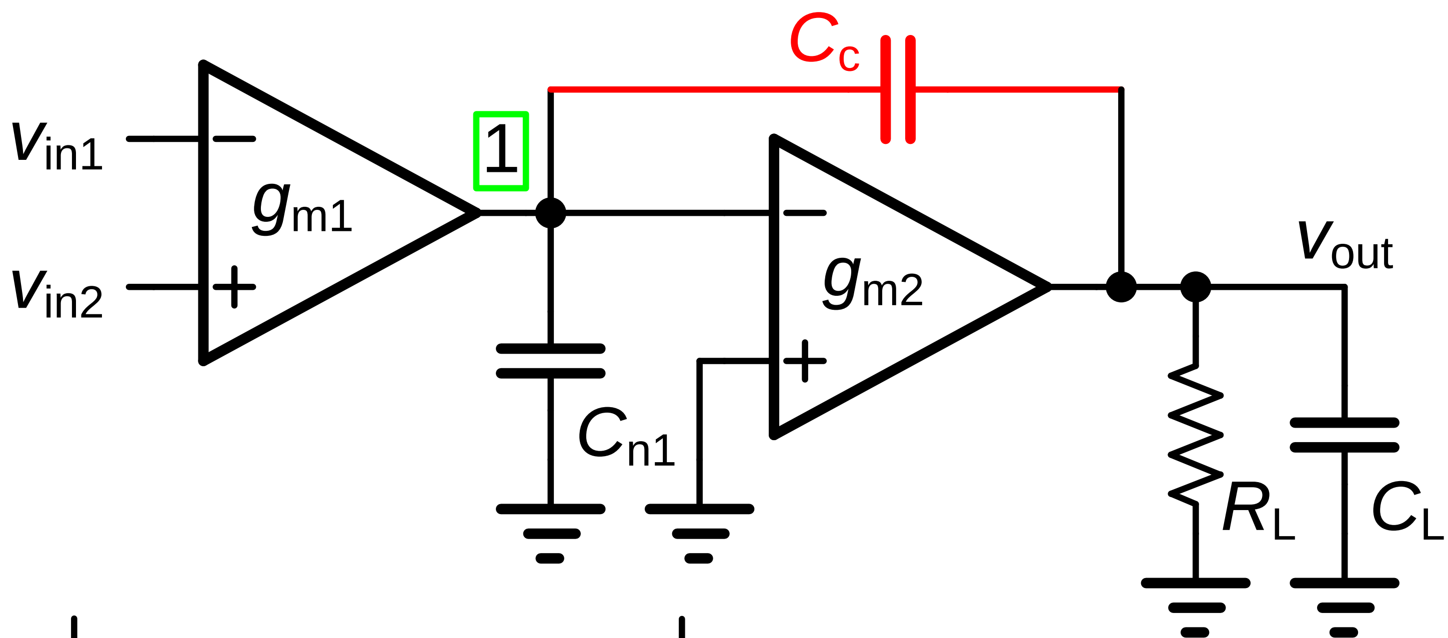


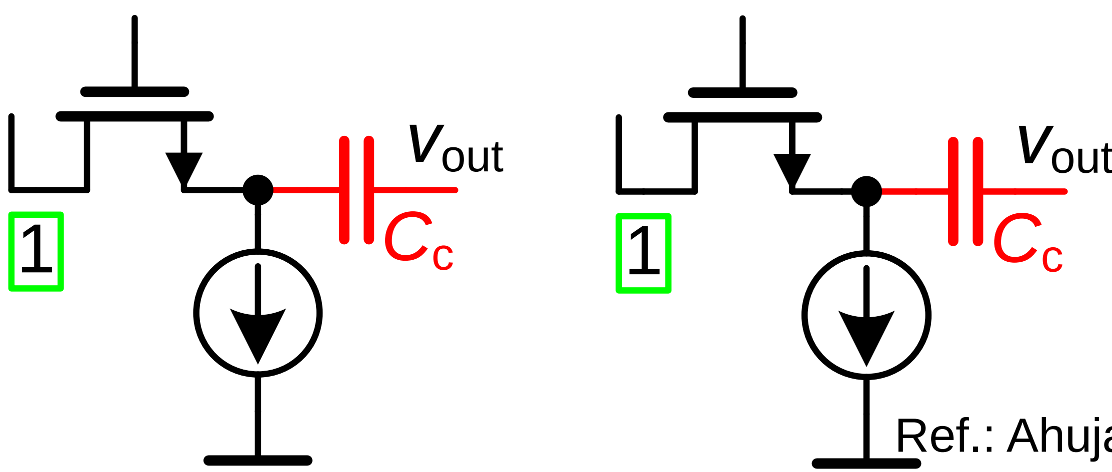


电压缓冲源极跟随器

Ref.: Tsividis, JSSC Dec.76, 748-753

截断正馈通路 2

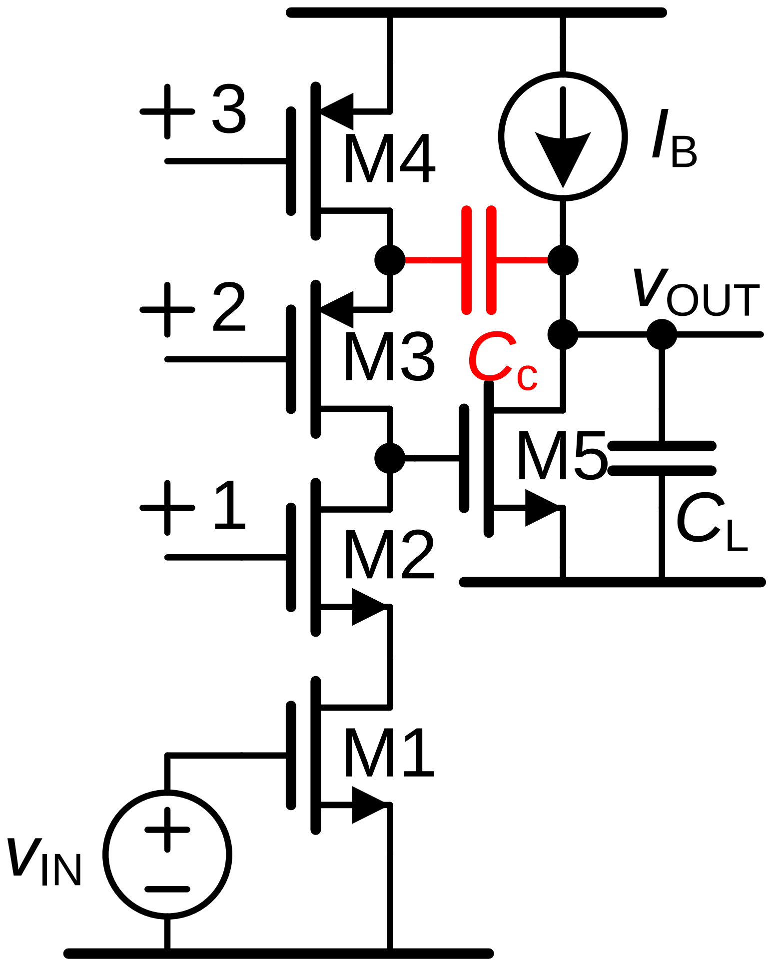


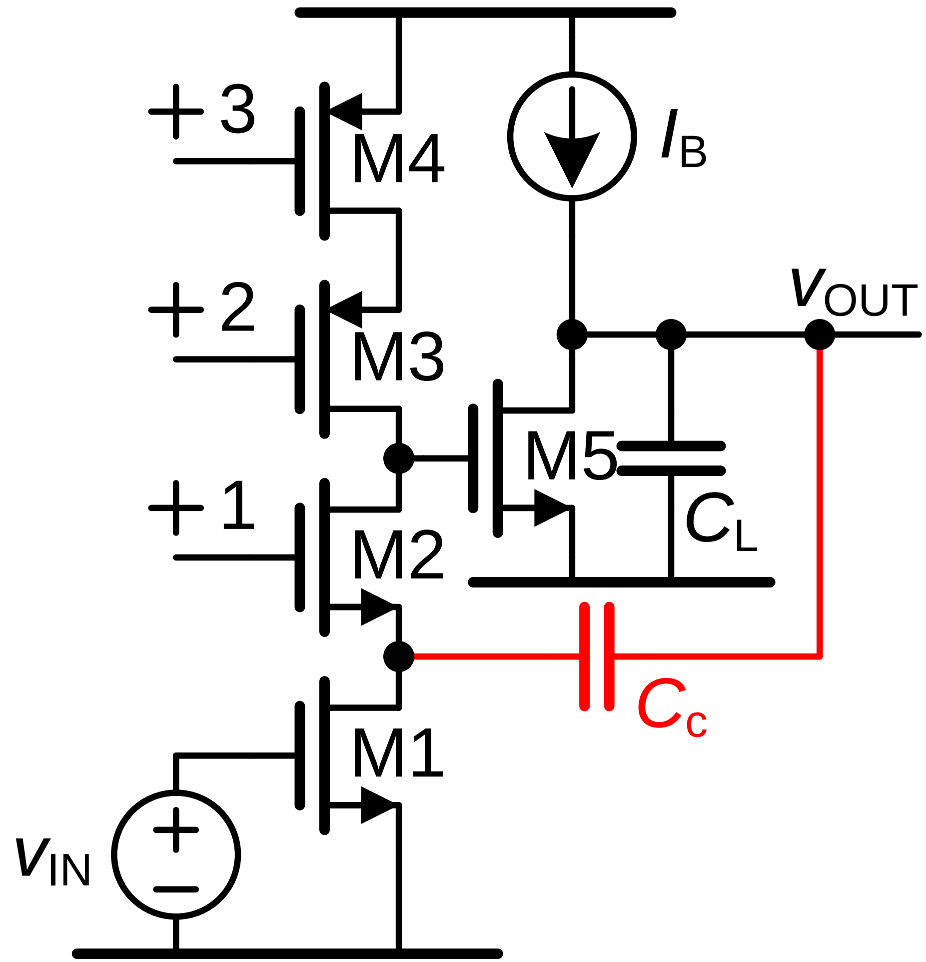


电流缓冲共源共栅

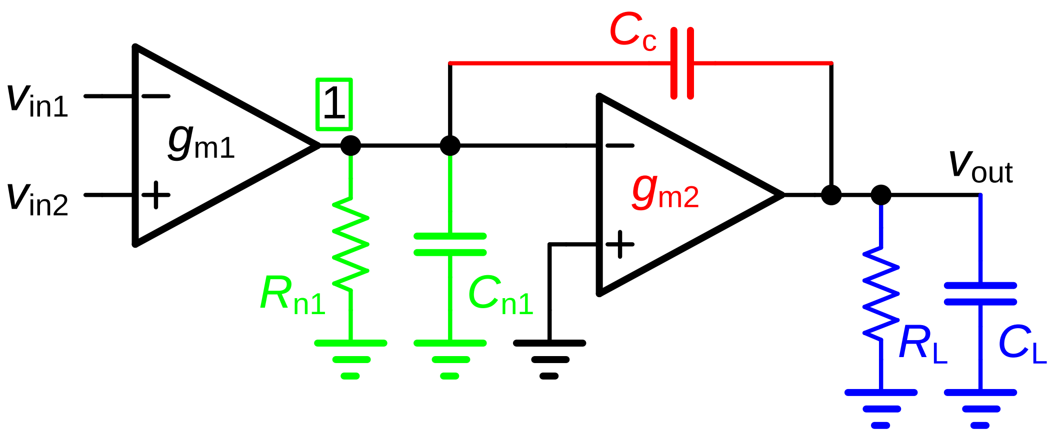
Ref.: Ahuja, JSSC Dec 83, 629-633

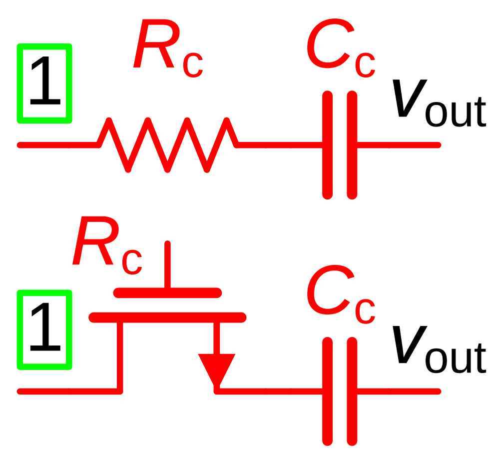
共源共栅密勒补偿


+3
M4
I_B
+2
M3
C_c
V_{OUT}
M5
+1
M2
C_L
M1
V_{IN}


+3
M4
I_B
+2
M3
V_{OUT}
M5
+1
M2
C_L
C_c
M1
V_{IN}

截断正馈通路 3





$$f_z = \frac{1}{2\pi C_c (1/g_{m2} - R_c)}$$

$R_c = 1/g_{m2}$ 无穷远处零点

$R_c > 1/g_{m2}$ 负零点

Ref.: Senderovics, JSSC Dec 78, 760-766

负零点补偿

$$R_c \gg 1/g_{m2} \quad \Rightarrow \quad f_z = -\frac{1}{2\pi C_c R_c}$$

$$f_z = 3GBW \quad \Rightarrow \quad R_c = \frac{1}{3g_{m1}}$$

选择 $$\boxed{\frac{1}{g_{m2}} < R_c < \frac{1}{3g_{m1}}}$$

练习：两级运放

已知: $GBW = 50\ \text{MHz}$、$C_L = 2\ \text{pF}$ 和 $V_{GS1} - V_T = 0.2\ \text{V}$

求: I_{DS1}、I_{DS2}、C_c 和 R_c

选择 $C_c = 1\ \text{pF} \Rightarrow g_{m1} = 2\pi C_c GBW = 315\ \mu\text{S}$

$$I_{DS1} = 31.5\ \mu\text{A} \quad 1/g_{m1} \approx 3.2\ \text{k}\Omega$$

$$f_{nd} = 150\ \text{MHz} \Rightarrow g_{m2} = 2\pi C_L 4GBW = 8g_{m1} = 2520\ \mu\text{S}$$

$$I_{DS2} = 252\ \mu\text{A} \quad 1/g_{m2} \approx 400\ \Omega$$

$$\frac{1}{g_{m2}} < R_c < \frac{1}{3g_{m1}} \Rightarrow 400\ \Omega < R_c < 1\ \text{k}\Omega$$

$$R_c \approx 400\sqrt{2.5} \approx 640\ \Omega \pm 60\%$$

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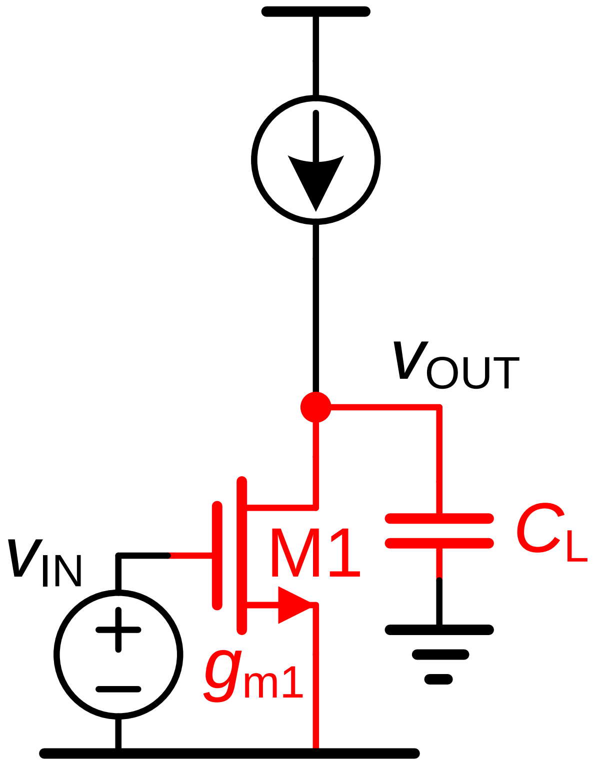
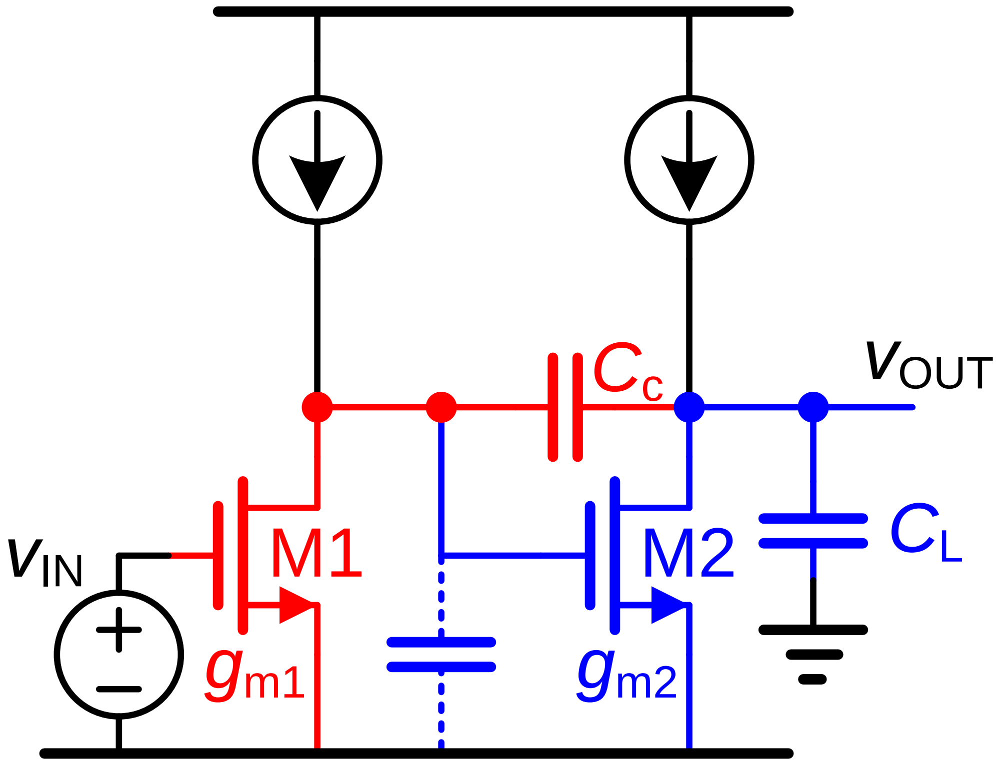
一级CMOS OTA



$$GBW = \frac{g_{m1}}{2\pi C_L}$$

两级密勒CMOS OTA

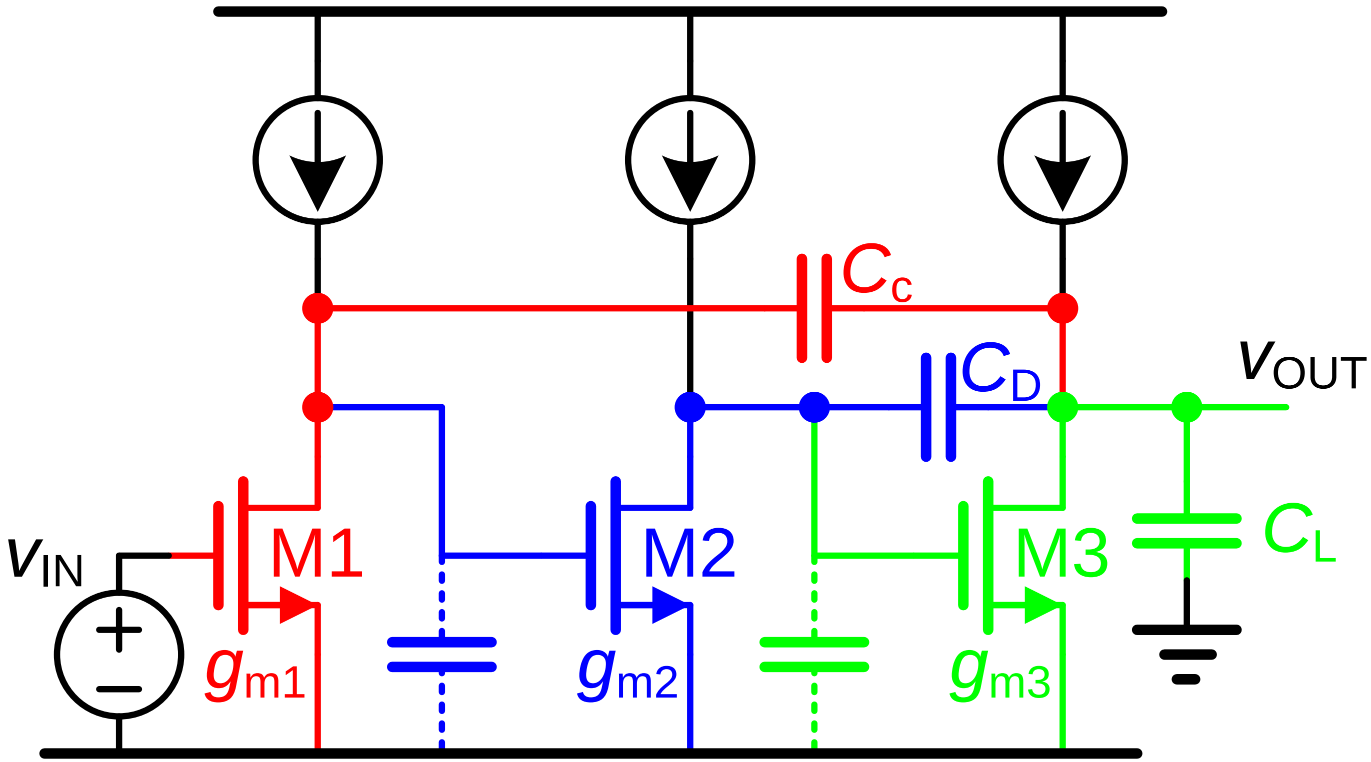


$$GBW = \frac{g_{m1}}{2\pi C_c}$$

$$f_{nd1} = \frac{g_{m2}}{2\pi C_L}$$

$$f_{nd1} = 3GBW$$

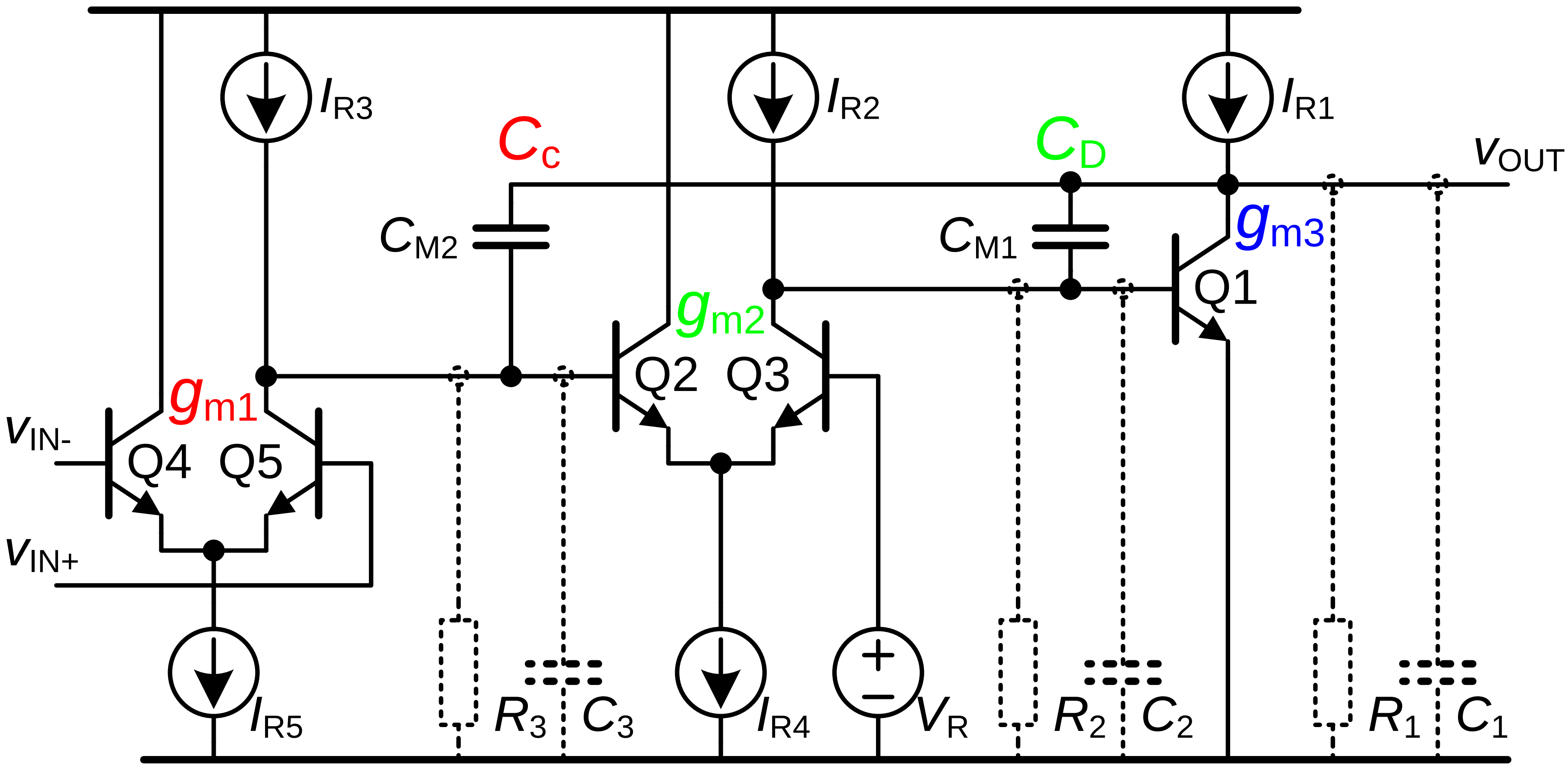
三级嵌套密勒CMOS OTA



$$GBW = \frac{g_{m1}}{2\pi C_c} \qquad f_{nd1} = \frac{g_{m2}}{2\pi C_D} \qquad f_{nd2} = \frac{g_{m3}}{2\pi C_L}$$

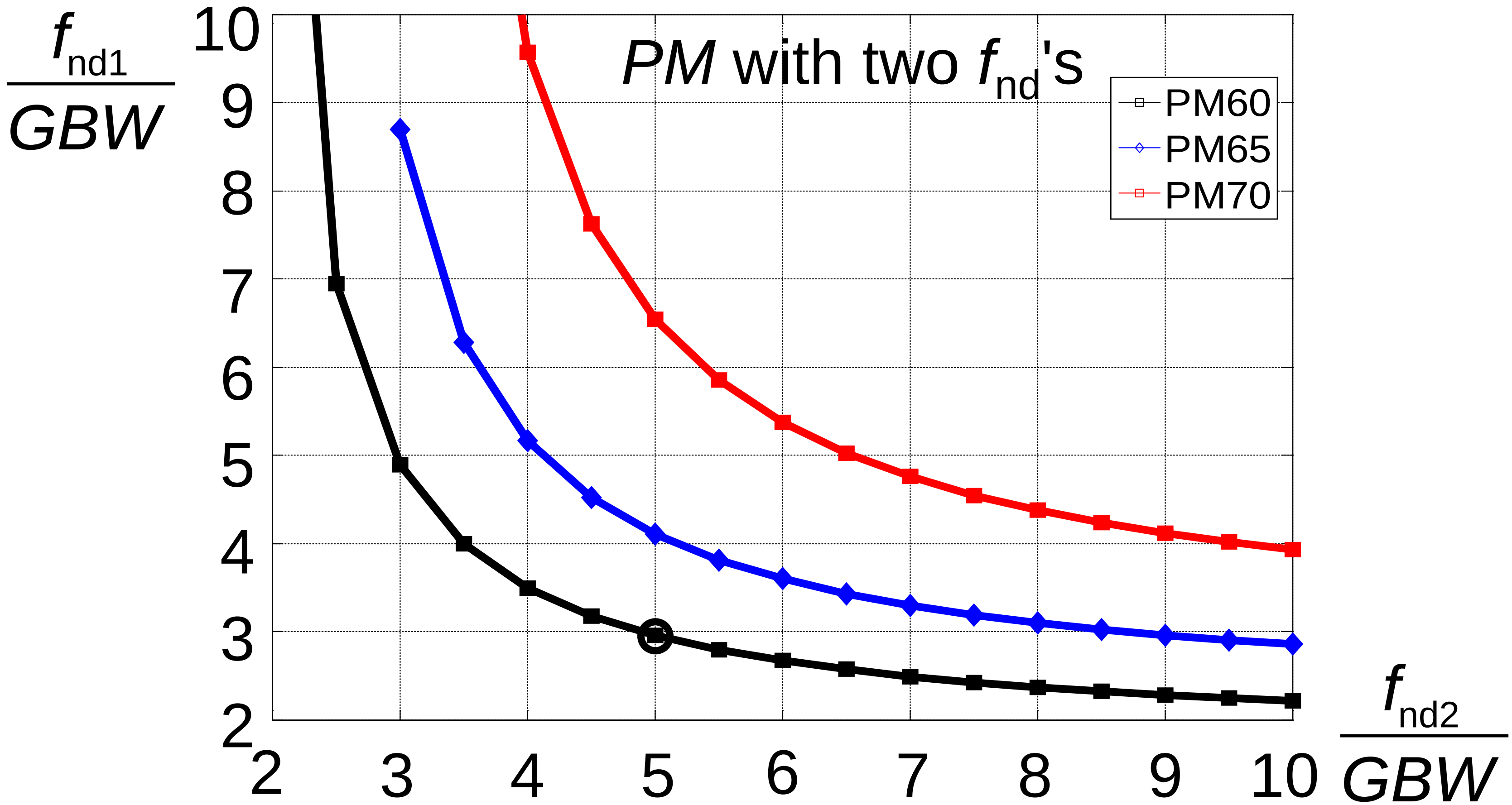
$$f_{nd1} = 3GBW \qquad f_{nd2} = 5GBW$$

差分对构建嵌套密勒OTA



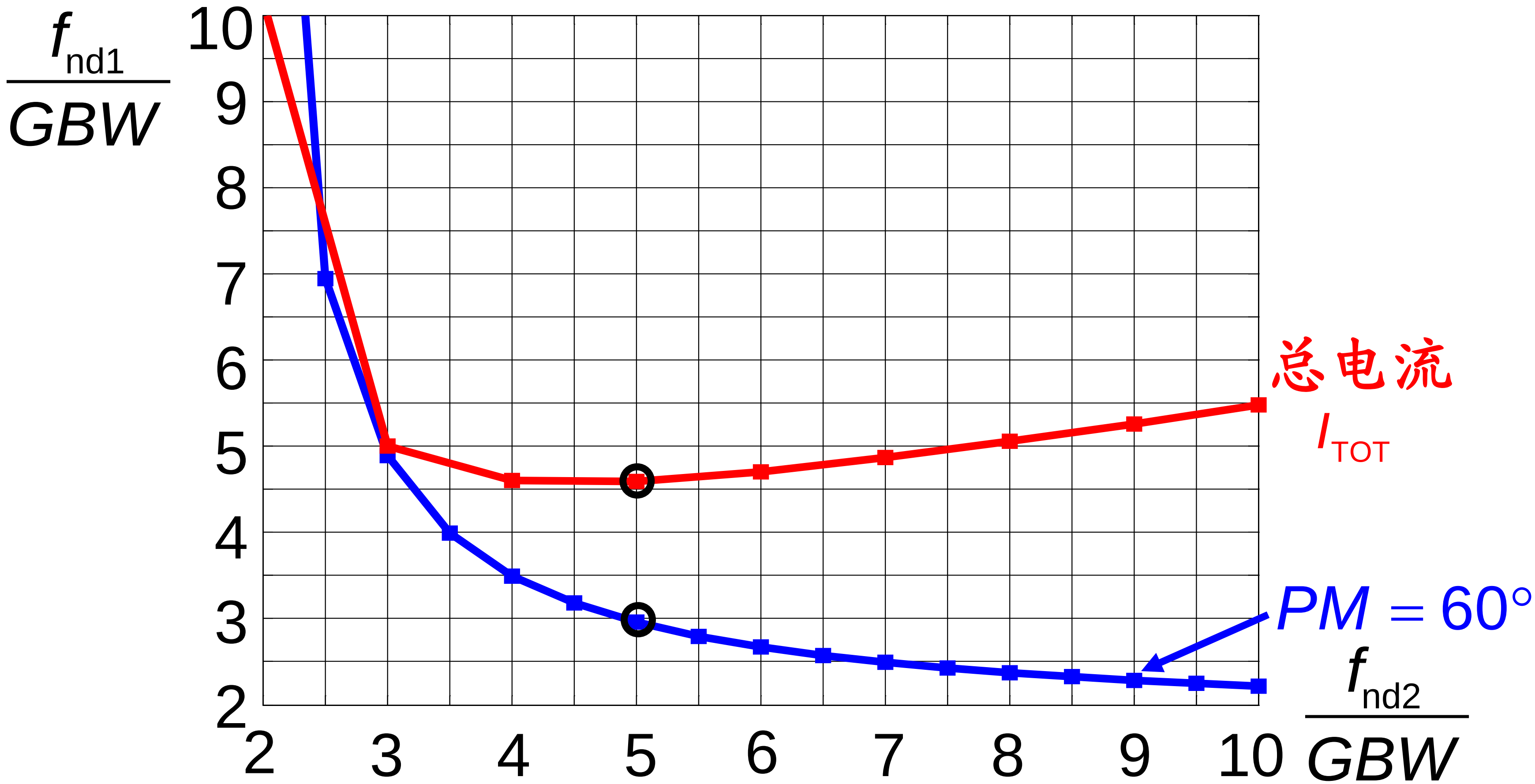
Ref.: Huijsing, JSSC Dec.85, pp.1144-1150

PM与两个非主极点的关系



$$PM = 90° - \arctan(\frac{GBW}{f_{nd1}}) - \arctan(\frac{GBW}{f_{nd2}})$$

功耗与两个非主极点的关系



$$I_{TOT}=2I_{DS1}+2I_{DS2}+I_{DS3}$$

三级运放的初步设计

$$GBW = \frac{g_{m1}}{2\pi C_c} \qquad f_{nd1} = \frac{g_{m2}}{2\pi C_D} \qquad f_{nd2} = \frac{g_{m3}}{2\pi C_L}$$

$$f_{nd1} = 3GBW \qquad f_{nd2} = 5GBW$$

选择 $C_D \approx C_c$ $\Rightarrow$ $\frac{g_{m2}}{g_{m1}} \approx 3$ $\qquad \frac{g_{m3}}{g_{m1}} \approx 5\frac{C_L}{C_c}$

输出级需要大电流!

练习：三级运放设计

已知: $GBW = 50\ \text{MHz}$、$C_L = 2\ \text{pF}$ 和 $V_{GS} - V_T = 0.2\ \text{V}$

求: I_{DS1}、I_{DS2}、I_{DS3}、C_c 和 C_D

选择 $C_c = C_D = 1\ \text{pF} \Rightarrow g_{m1} = 2\pi C_c GBW = 315\ \mu\text{S}$

$$I_{DS1} = 31.5\ \mu\text{A}$$

$$f_{nd1} = 150\ \text{MHz} \Rightarrow g_{m2} = 2\pi C_D 3GBW = 3g_{m1} = 945\ \mu\text{S}$$

$$I_{DS2} = 94.5\ \mu\text{A}$$

$$f_{nd2} = 250\ \text{MHz} \Rightarrow g_{m3} = 2\pi C_L 5GBW = 10g_{m1} = 3150\ \mu\text{S}$$

$$I_{DS3} = 315\ \mu\text{A}$$

一/两/三级运放的比较

$GBW = 50\ \text{MHz} \quad C_L = 2\ \text{pF}$

单级：$I_{DS1} = 31.5\ \mu\text{A}$

$I_{TOT} = 2I_{DS1} = 63\ \mu\text{A}$

两级：选择 $C_c = 1\ \text{pF} \quad I_{DS1} = 31.5\ \mu\text{A} \quad I_{DS2} = 252\ \mu\text{A}$

$I_{TOT} = 2I_{DS1} + I_{DS2} = 315\ \mu\text{A}$

三级：选择 $C_c = C_D = 1\ \text{pF}$

$I_{DS1} = 31.5\ \mu\text{A} \quad I_{DS2} = 94.5\ \mu\text{A} \quad I_{DS3} = 315\ \mu\text{A}$

$I_{TOT} = 2I_{DS1} + 2I_{DS2} + I_{DS3} = 576\ \mu\text{A}$