

CMOS模拟集成电路设计

第四章：运放的稳定性与系统性设计

胡远奇

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运放的稳定性与系统性设计

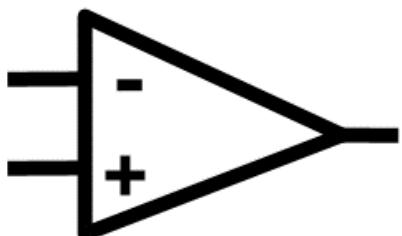
- **运放、反馈与稳定性**的基本概念
- 极点分离与零点补偿
- 三级运放稳定性问题简介
- 运放的系统性设计方法
- 运放的其他参数指标



运算放大器的分类

Opamp

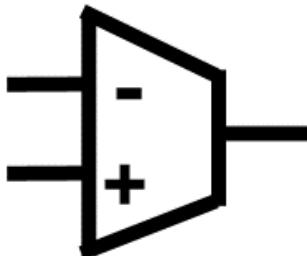
Operational
amplifier



$$A_v = \frac{v_{\text{OUT}}}{v_{\text{IN}}}$$

OTA

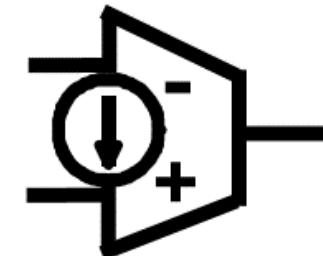
Operational
Transconduct.
amplifier



$$A_g = \frac{i_{\text{OUT}}}{v_{\text{IN}}}$$

OCA

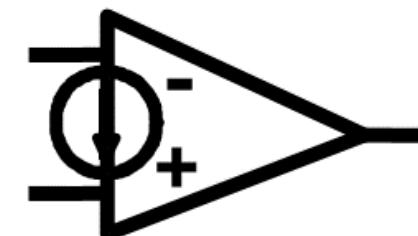
Operational
Current
amplifier



$$A_i = \frac{i_{\text{OUT}}}{i_{\text{IN}}}$$

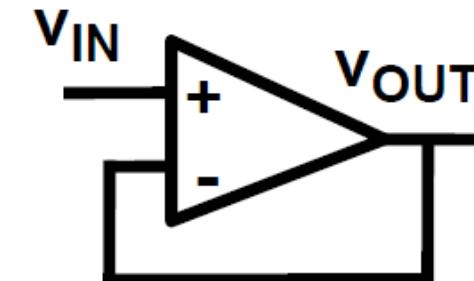
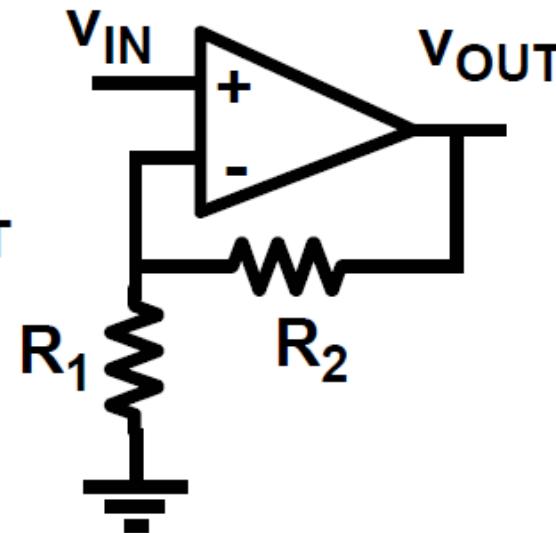
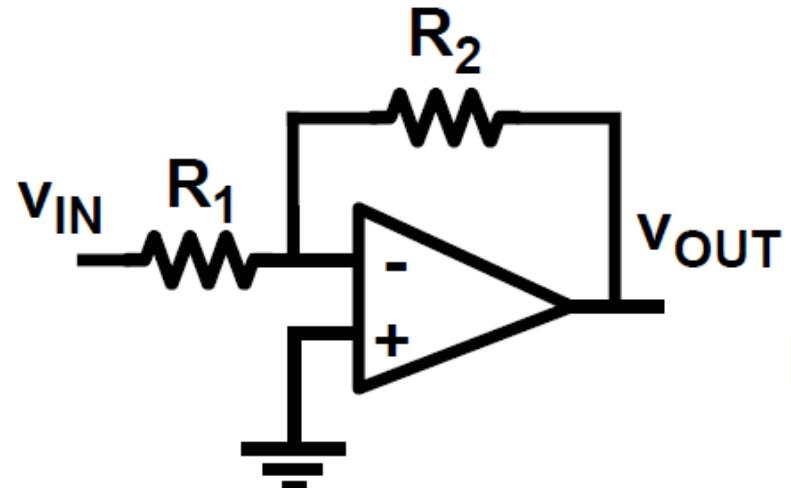
CM amp

Current
Mode
amplifier



$$A_r = \frac{v_{\text{OUT}}}{i_{\text{IN}}}$$

» 负反馈配置



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

$$R_{IN} = R_1$$

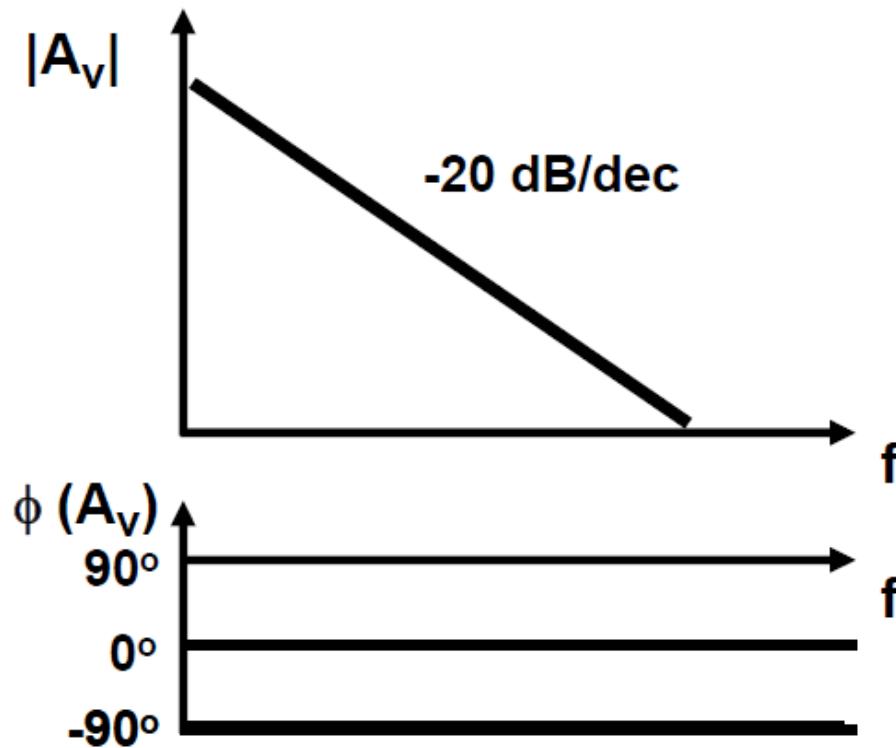
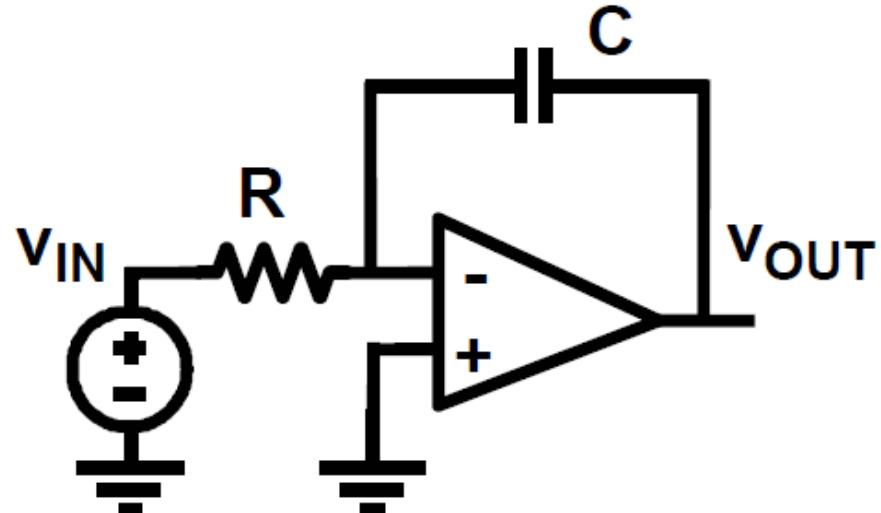
$$A_v = 1 + \frac{R_2}{R_1}$$

$$R_{IN} = \infty$$

$$A_v = 1$$

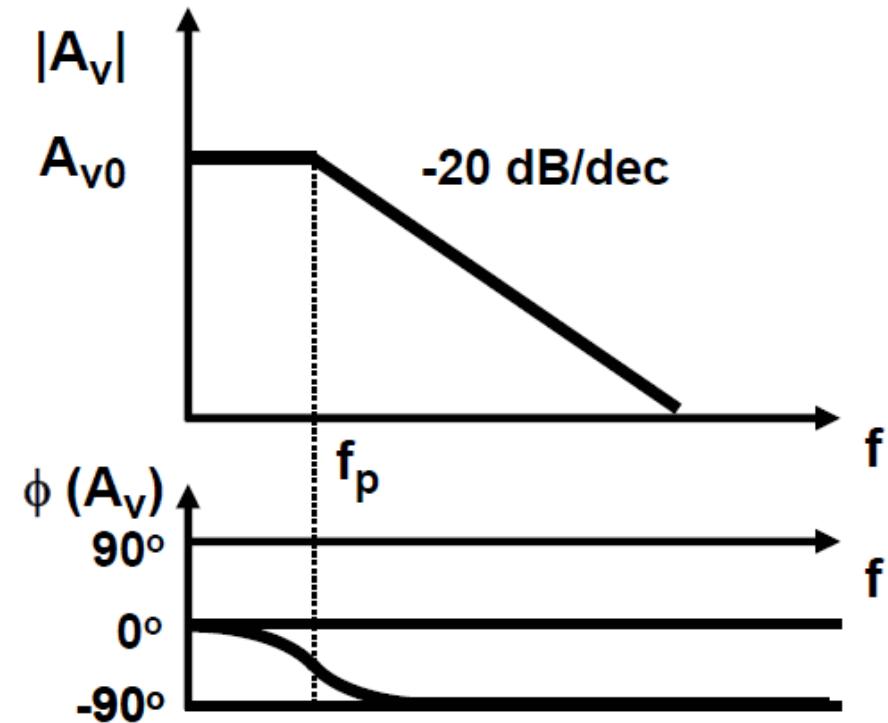
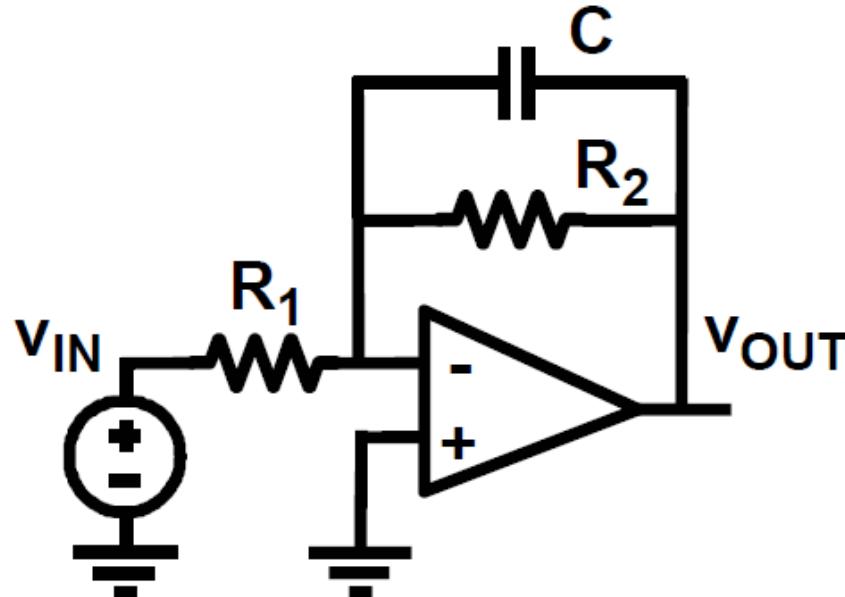
$$R_{IN} = \infty$$

» 积分器 (Integrator)



□ 假设运放为理想运放，当 V_{IN} 为一个1V的阶跃输入信号时，画出输出 V_{OUT} 的。

低通濾波器 (Low-pass Filter / Lossy Integrator)



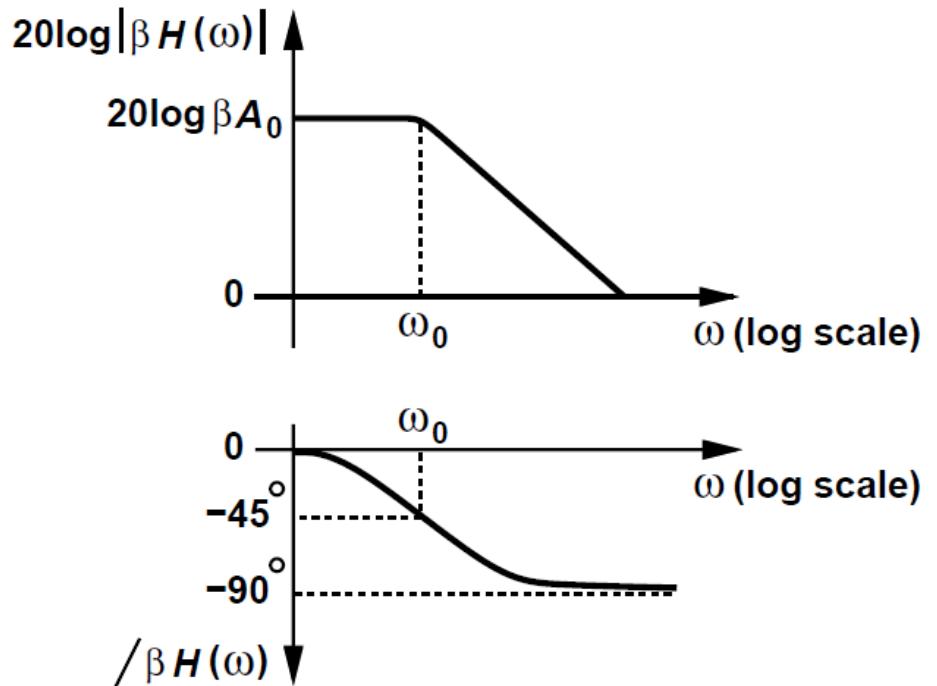
$$A_{v0} = - \frac{R_2}{R_1}$$

$$A_v = \frac{A_{v0}}{\left(1 + j \frac{f}{f_p}\right)}$$

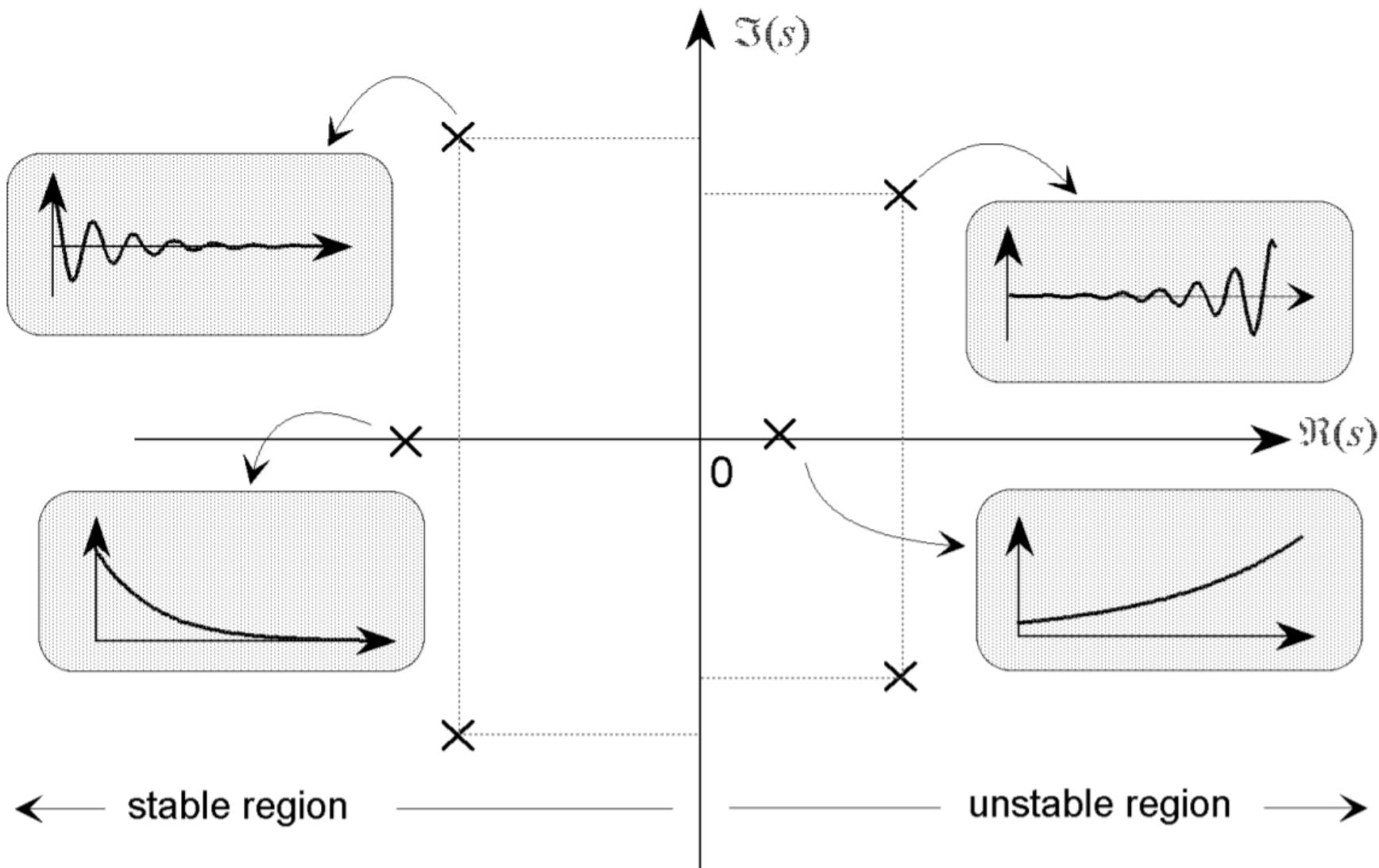
$$f_p = \frac{1}{2\pi R_2 C}$$

波特图

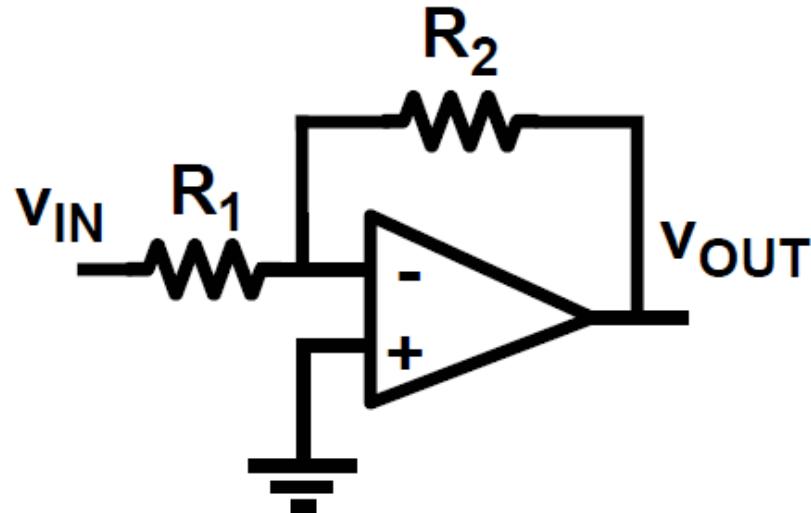
- **幅度**曲线的斜率在每个零点处变化+20dB/dec，在每个极点处变化-20dB/dec。
- **相位**在极点频率的1/10处变化，在极点处经历-45度的变化，并且在10倍极点处达到-90度的变化。
- 相位变化的速度**快于**幅度变化。



» 极点对系统的影响



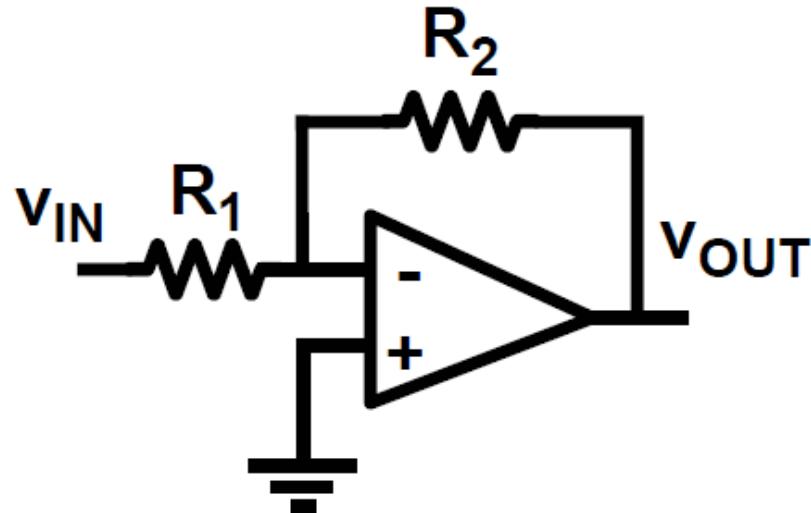
»» 增益与带宽的交换



□ 假设运放的增益带宽积为 GBW_0 ，
该反馈电路带宽为多少？

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

» 增益与带宽的交换



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

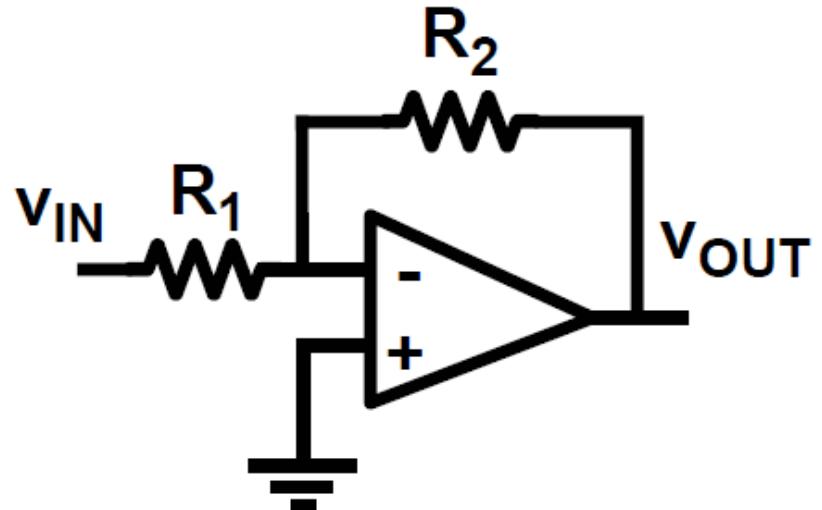
□ 假设运放的增益带宽积为 GBW_0 ,
该反馈电路带宽为多少?

$$A(s) = \frac{A_0}{\left(1 + \frac{s}{\omega_0}\right)}$$

$$H(s) = \frac{A_0 R_2}{A_0 R_1 + R_1 + R_2 + \frac{s(R_1 + R_2)}{\omega_0}}$$

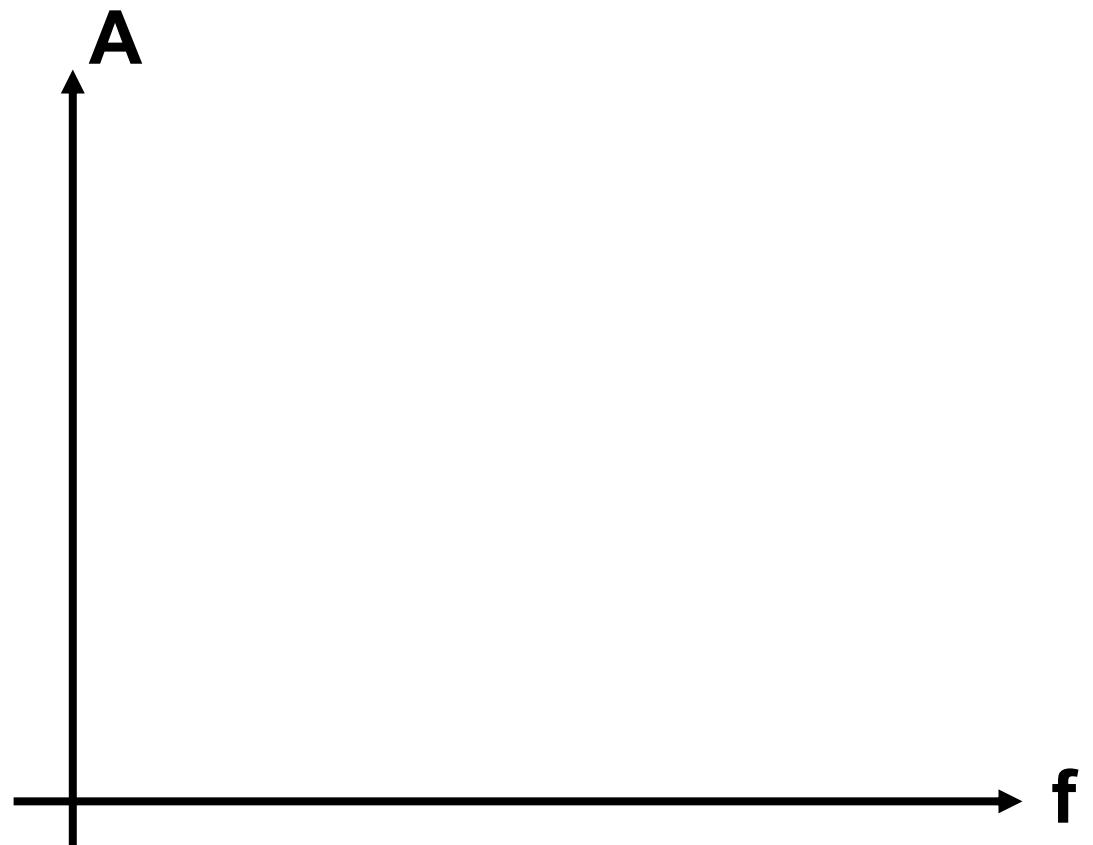
$$p'_d \approx \frac{A_0 \omega_0 \cdot R_1}{R_1 + R_2} = 2\pi GBW_0 \frac{R_1}{R_1 + R_2}$$

» 增益与带宽的交换



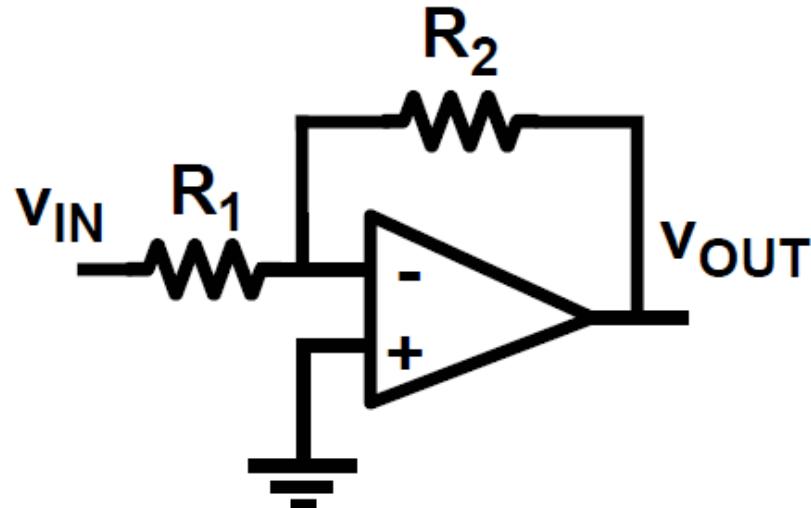
$$A_v = - \frac{R_2}{R_1}$$

GBW不变!



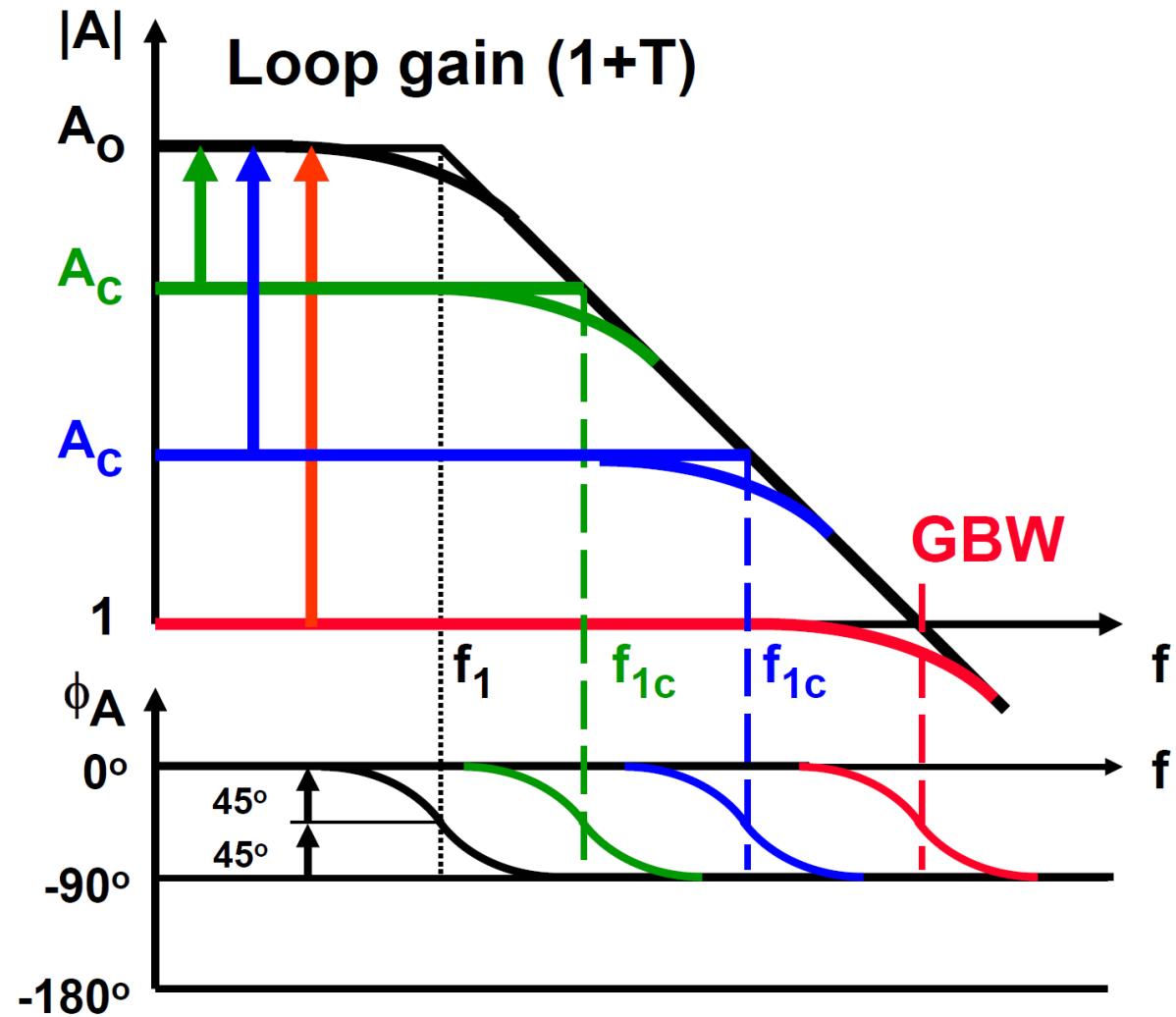
$$p'_d \approx \frac{A_0 \omega_0 \cdot R_1}{R_1 + R_2} = GBW_0 \frac{R_1}{R_1 + R_2}$$

》》 增益与带宽的交换

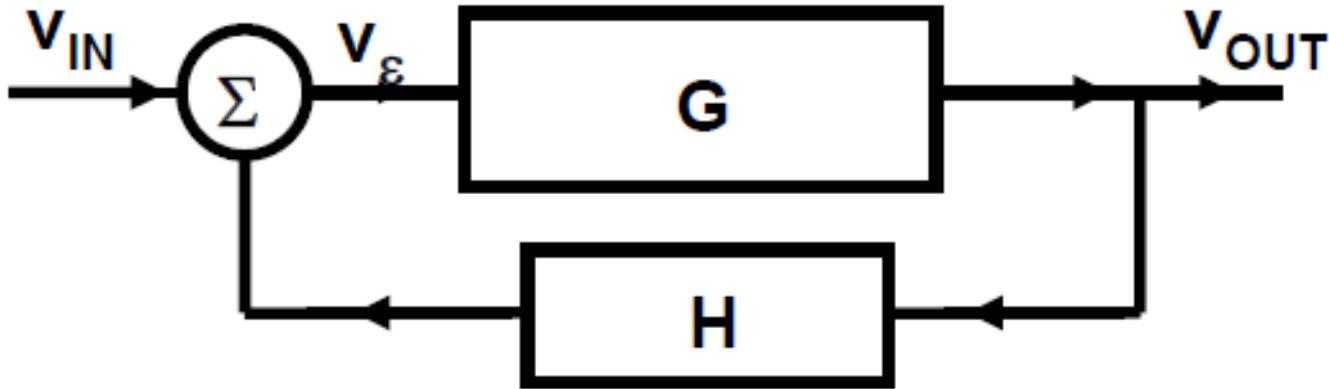


$$A_v = - \frac{R_2}{R_1}$$

GBW不变!

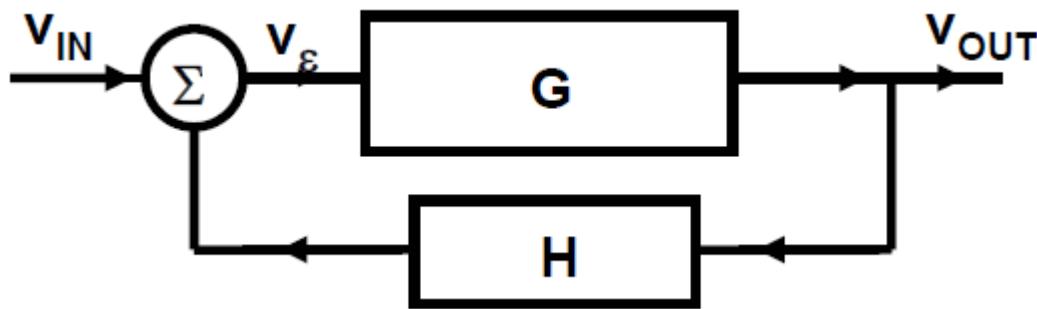
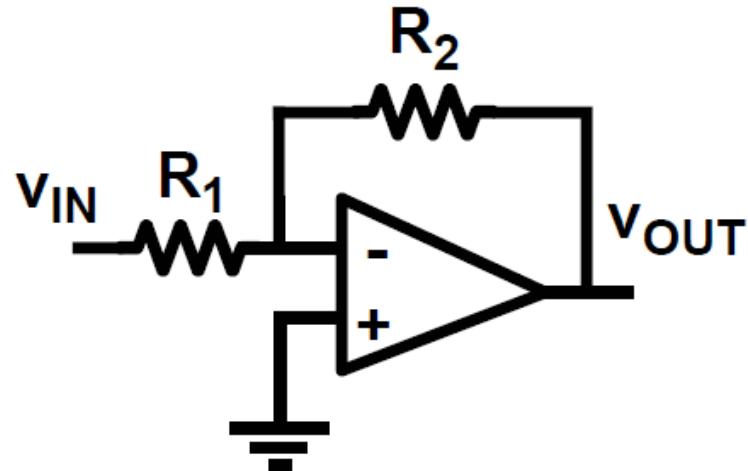


»» 开环与闭环增益



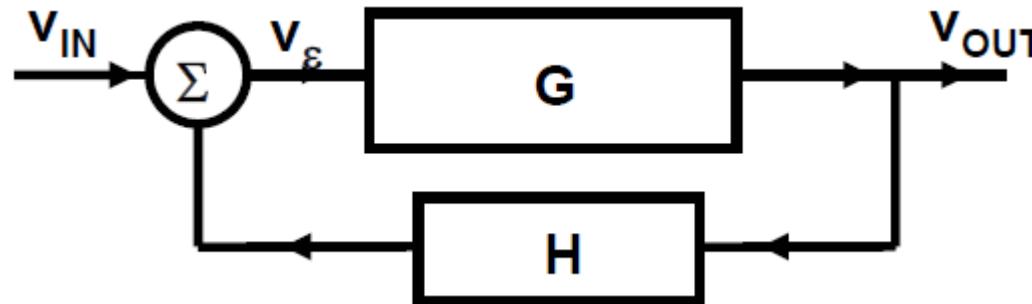
- **闭环**增益: $A_c = \frac{V_{OUT}}{V_{IN}} = \frac{G}{1 + GH}$
- **开环**增益: $A_o = G$
- **环路**增益: $A_L = GH$ ← **决定了反馈系统的所有特性!**

»» 开环与闭环增益



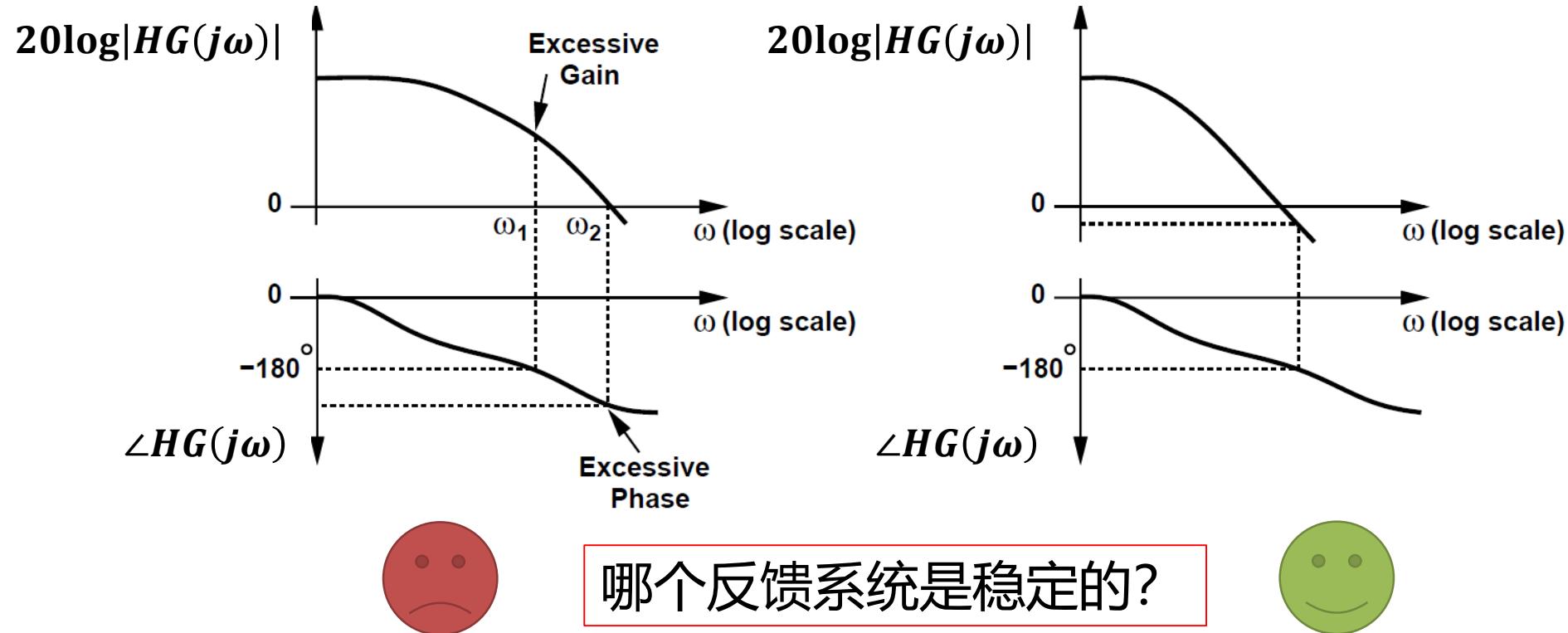
- **闭环增益:** $A_c = -R_2/R_1$ $H = R_1/(R_2 + R_1)$
- **开环增益:** $A_o = A_0$
- **环路增益:** $A_L = A_0 R_1/(R_2 + R_1)$ ← 通过反馈改变环路增益

» 反馈的稳定性判据



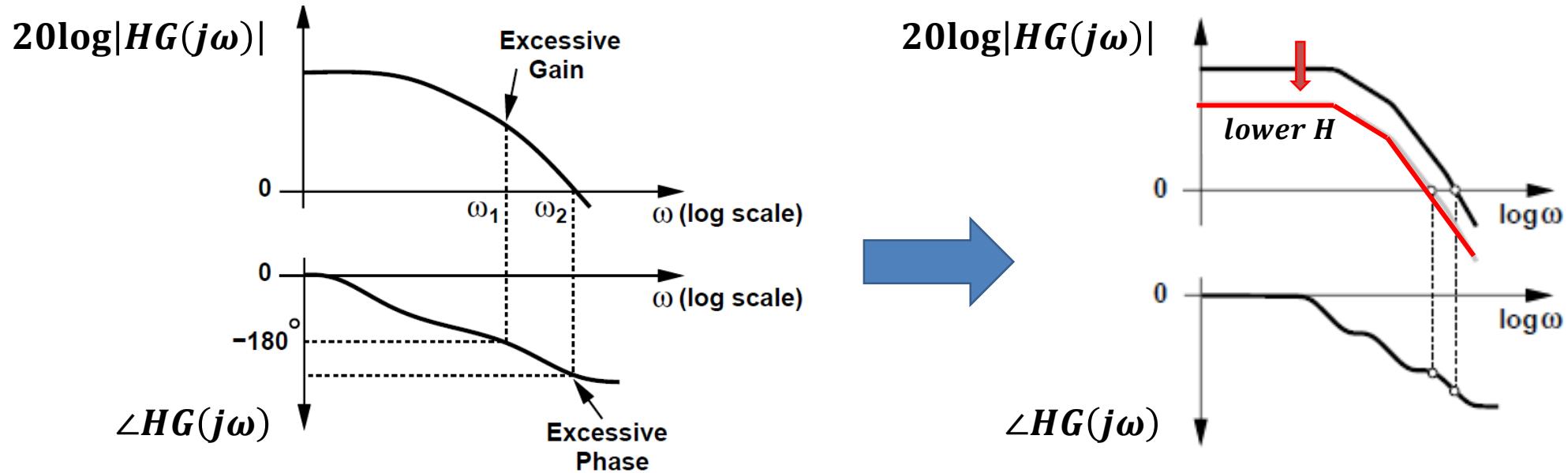
- 反馈系统存在潜在的不稳定性，并且可能会发生振荡。
- 闭环传递函数：
$$\frac{V_{OUT}}{V_{IN}}(s) = \frac{G(s)}{1 + HG(s)}$$
- “巴克豪森判据” -》 如果分母变为0会发生什么 $|HG(j\omega)| = 1$
 $\angle HG(j\omega) = -180^\circ$
- 负反馈本身提供 180° 相移

» 稳定性判定



- 增益为1和相位为-180度时的频率点分别称为“增益交点(GX)”和“相位交点(PX)”。
- PX必须落后于GX， GX等于开环系统中的单位增益带宽

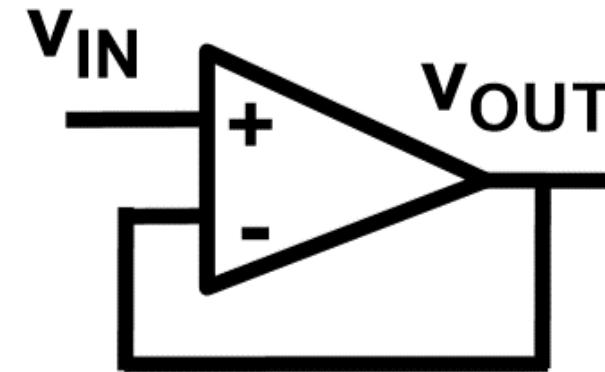
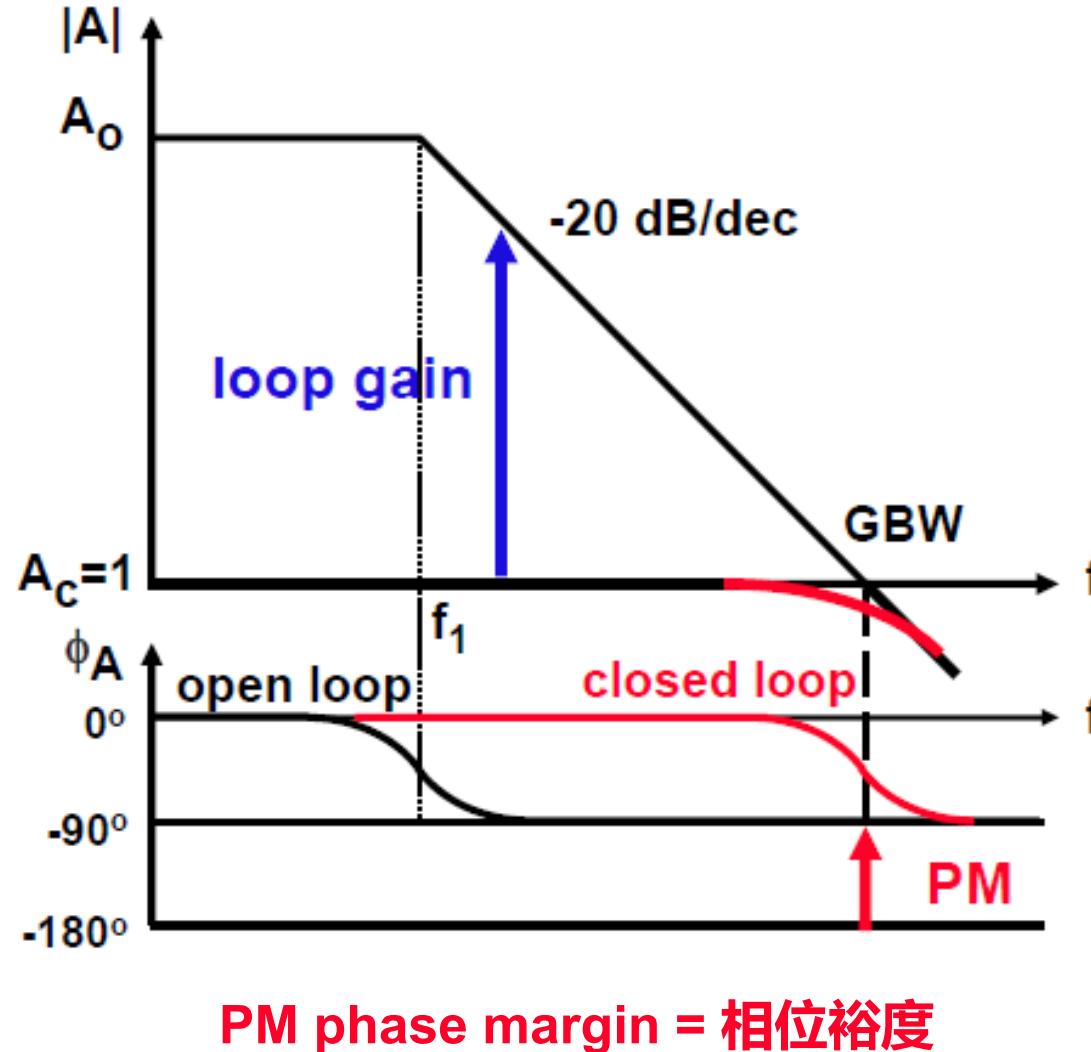
例1



□ 如果反馈系数减小，之前描述的系统是变得更稳定还是更不稳定？

解：如果 β 减少，使 $20\log\angle HG(\omega)$ 的图下移， G_X 向左移。由于相位不变，系统变得更稳定。

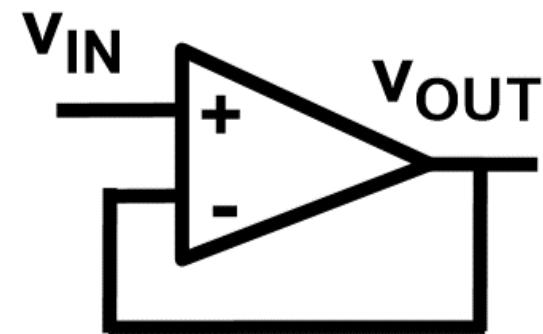
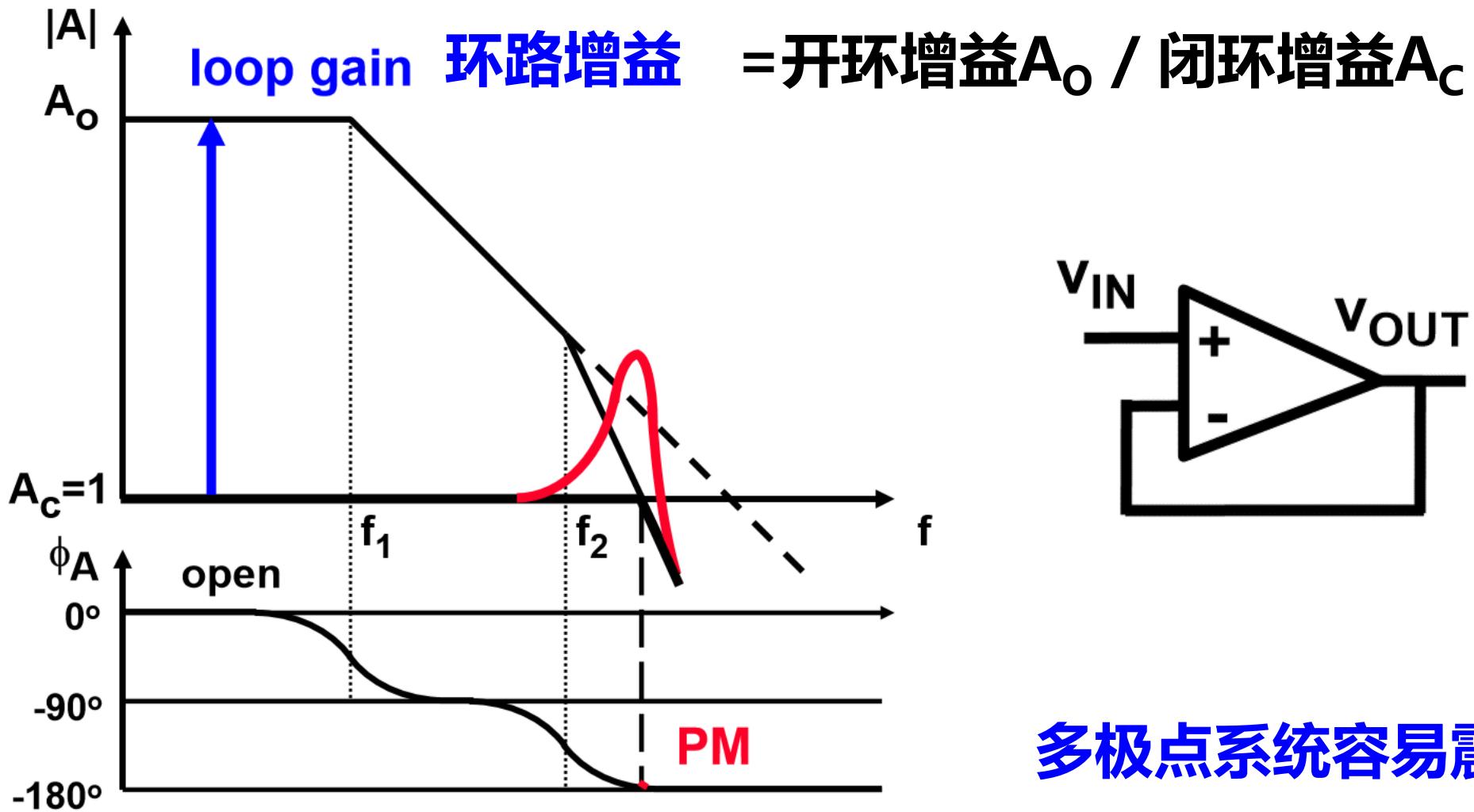
» 单极点系统



- 闭环增益=1
- 开环增益= A_0

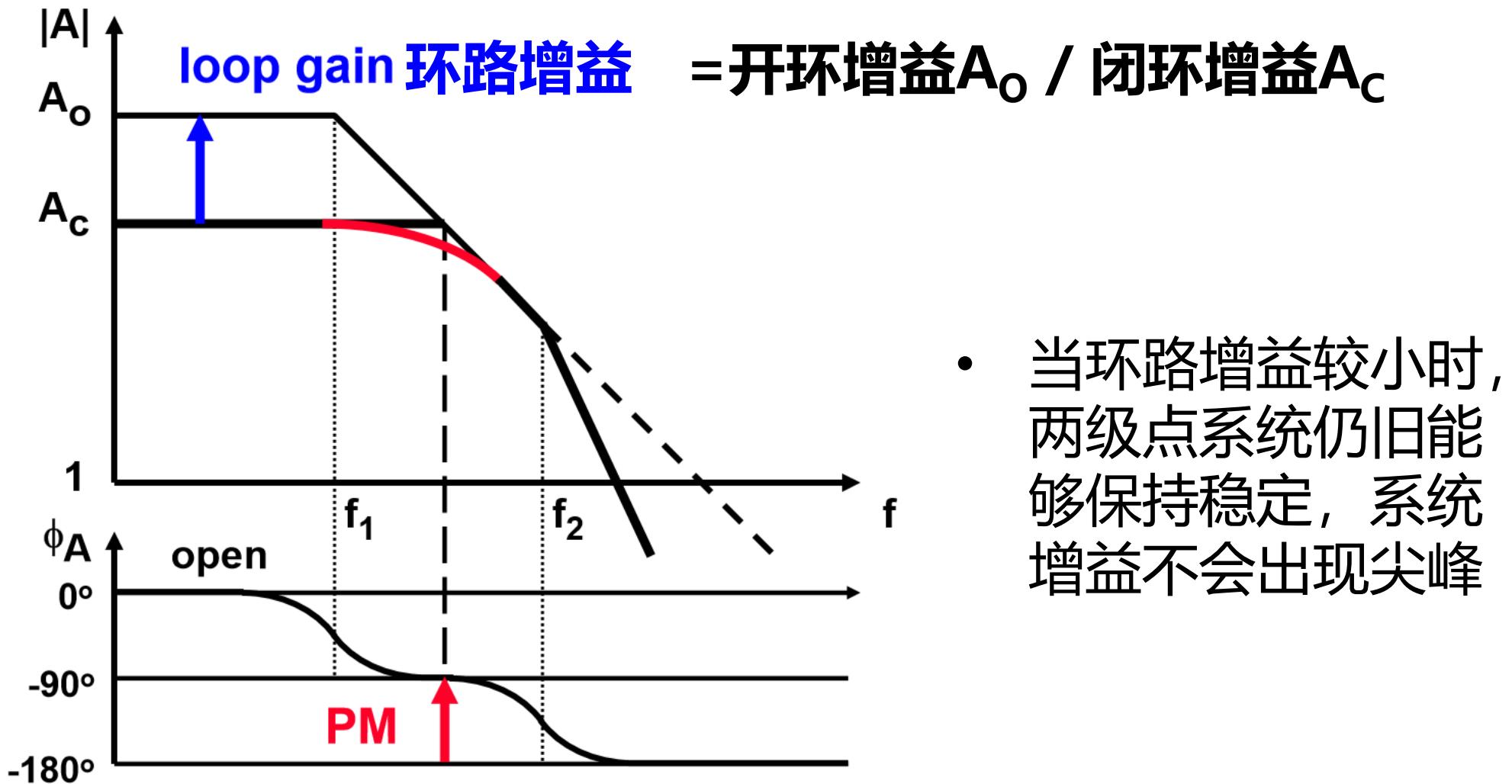
单极点系统天然稳定

》》两极点系统

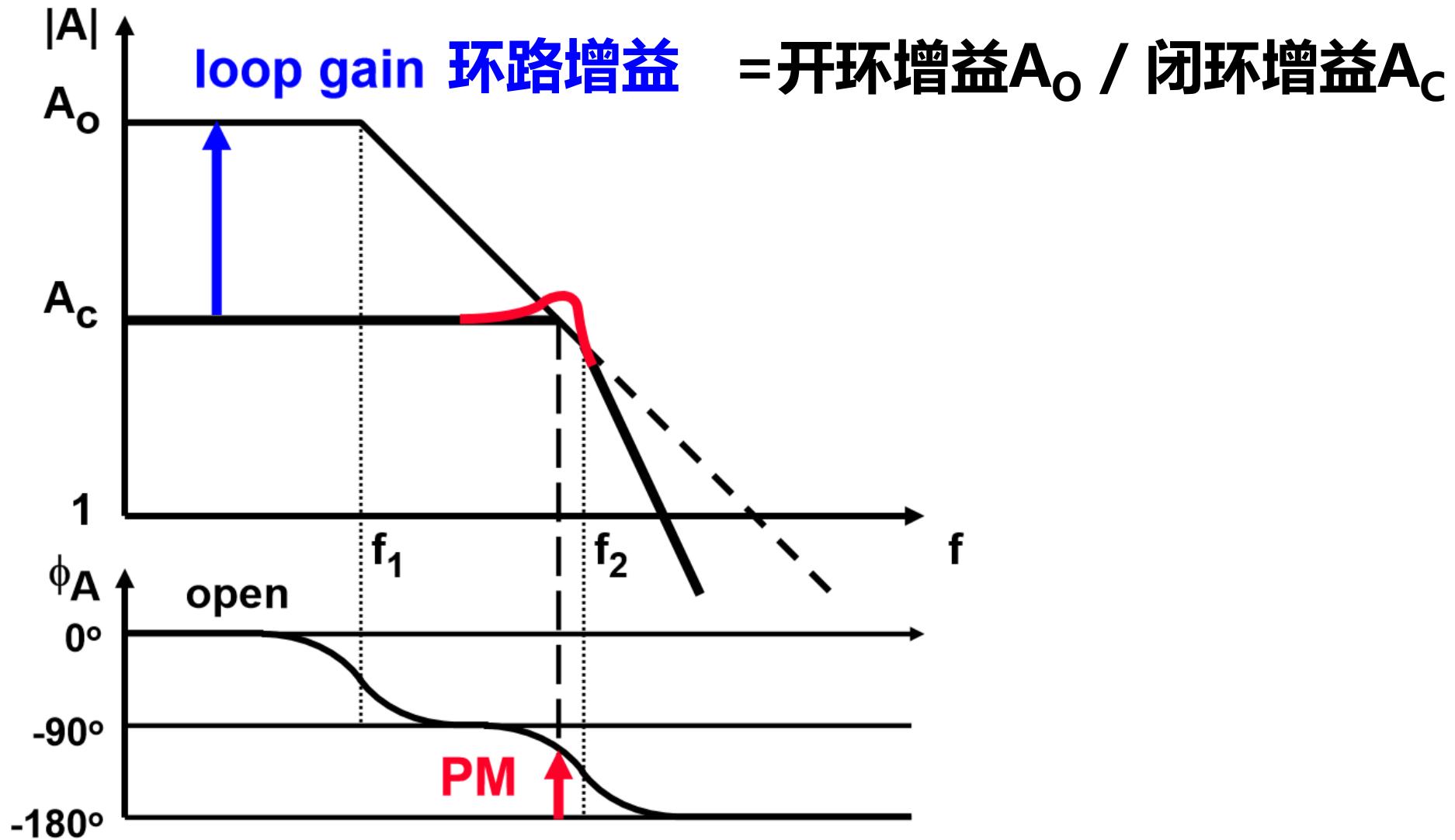


多极点系统容易震荡

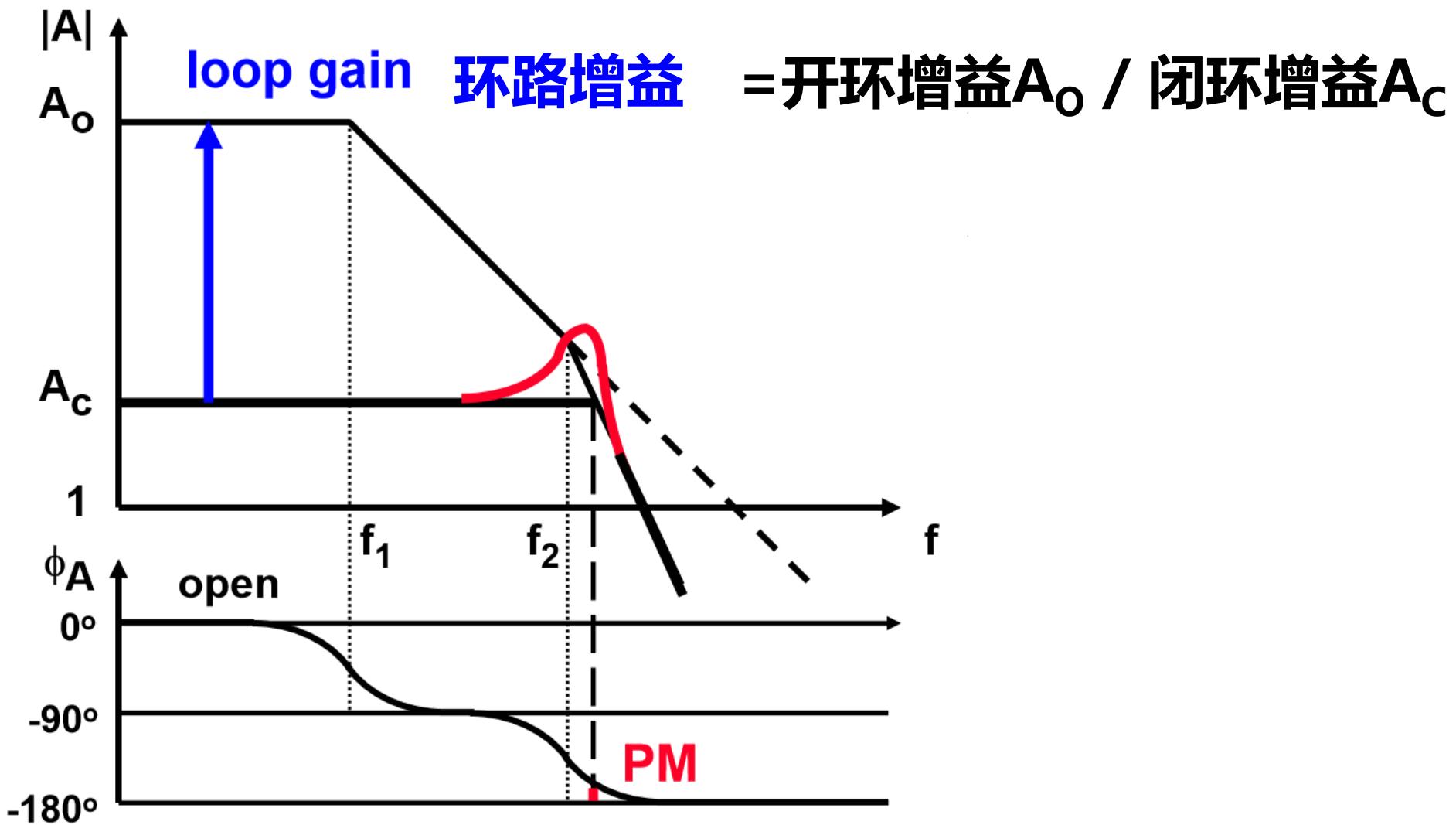
》》两极点系统



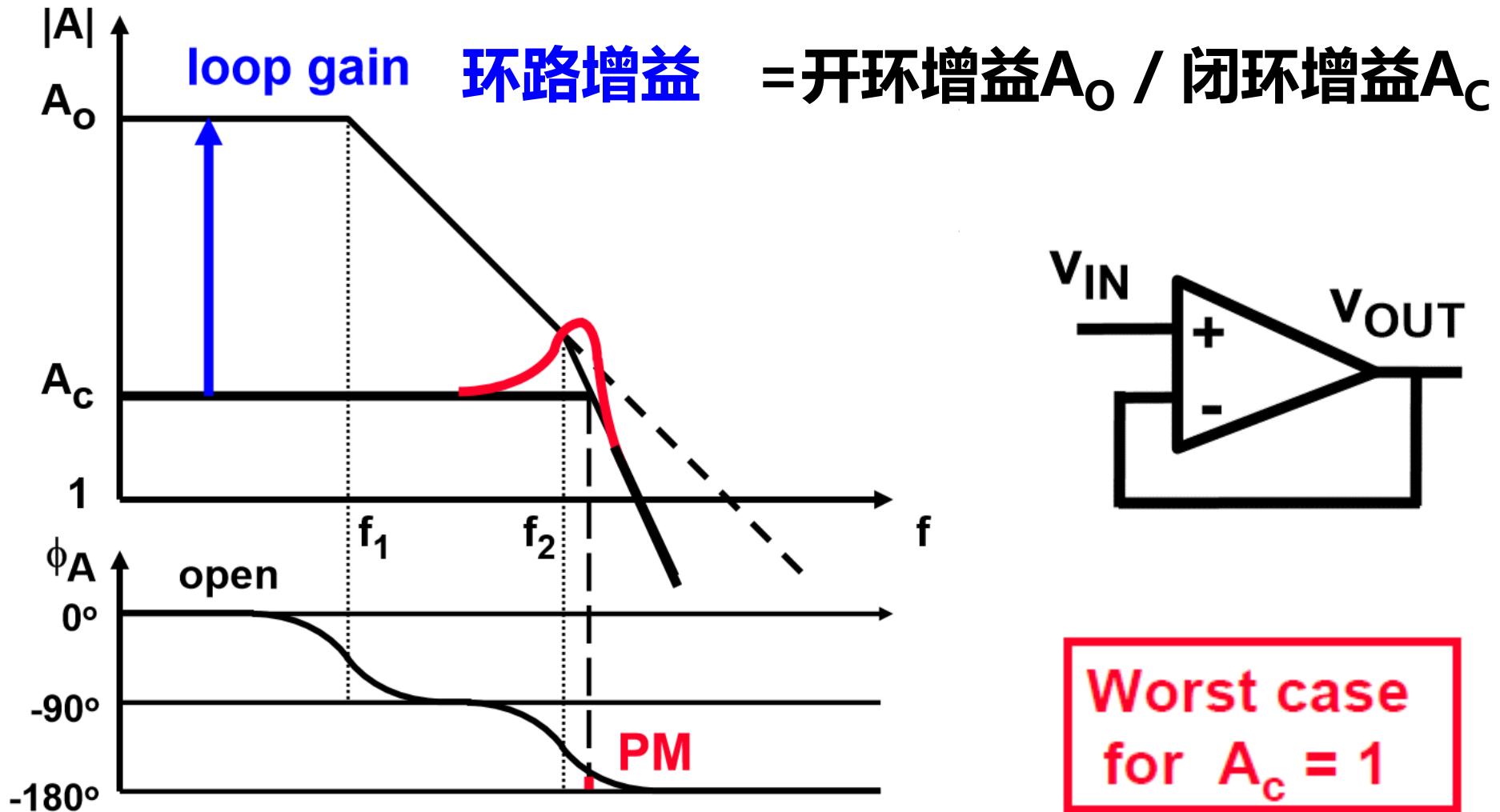
》》两极点系统



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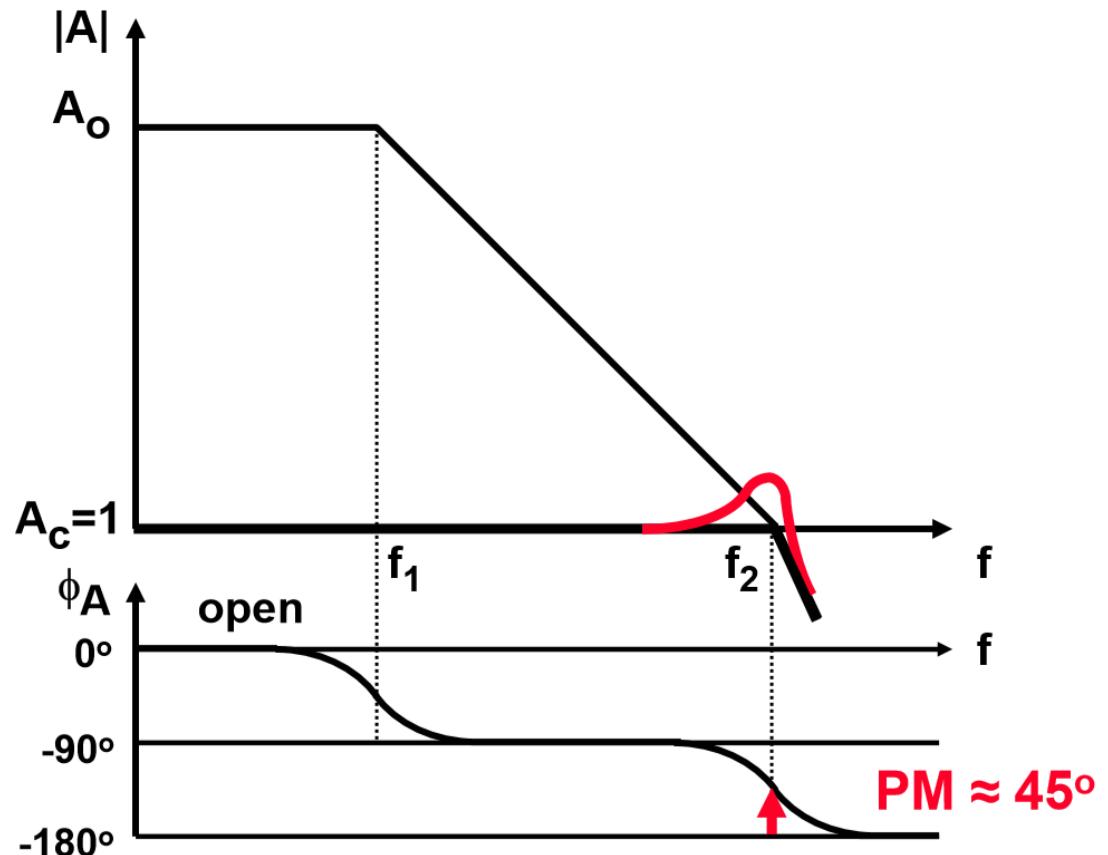
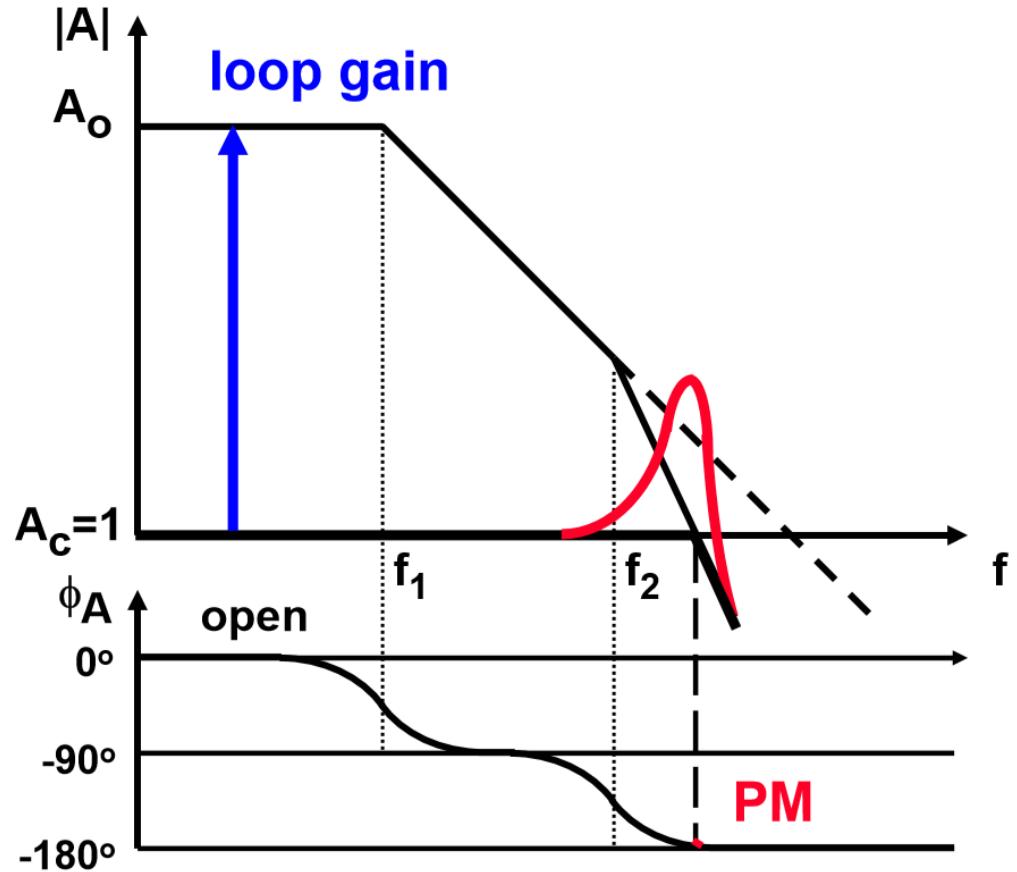


》》两极点系统



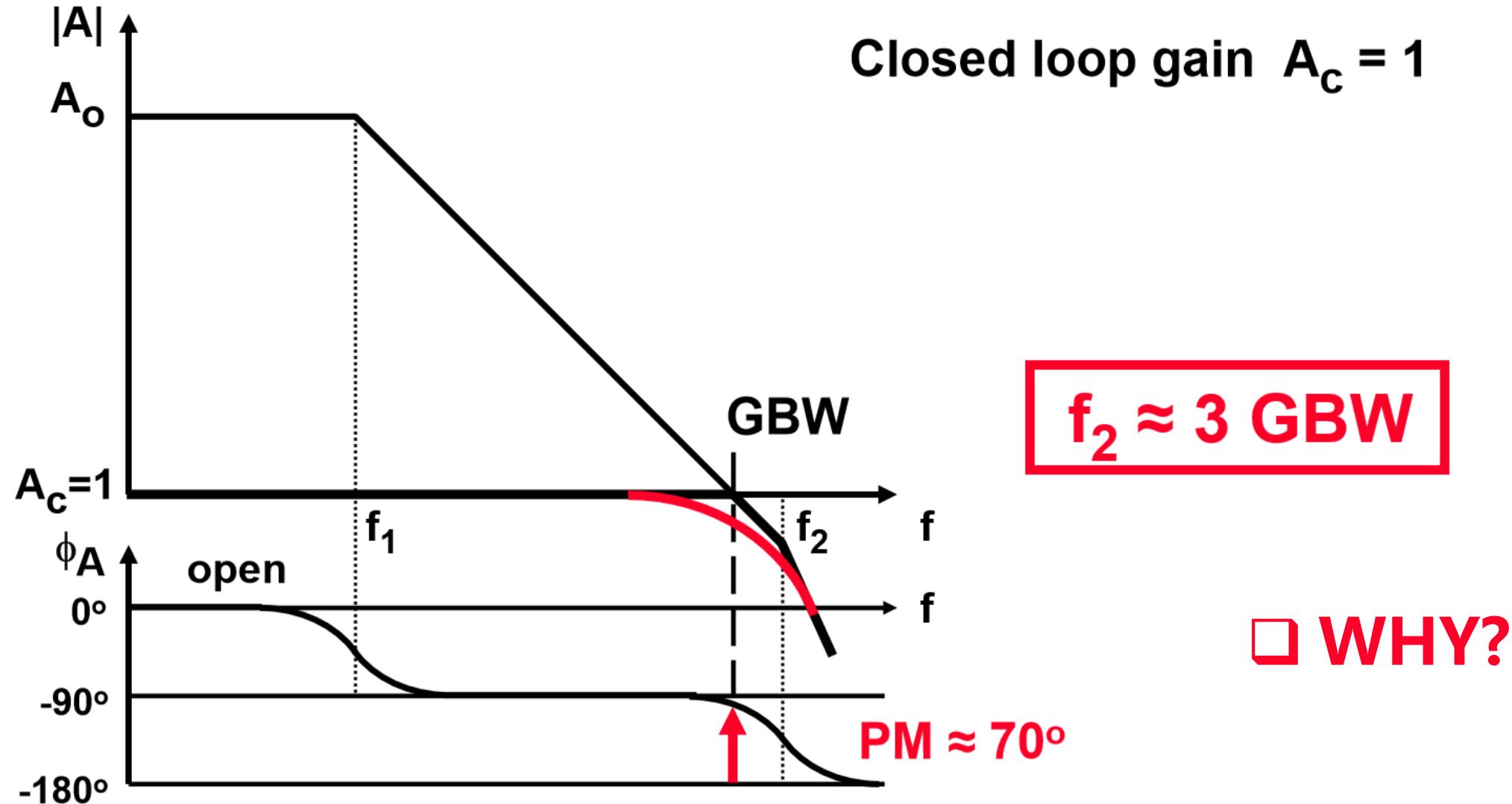


两极点系统：推远非主极点



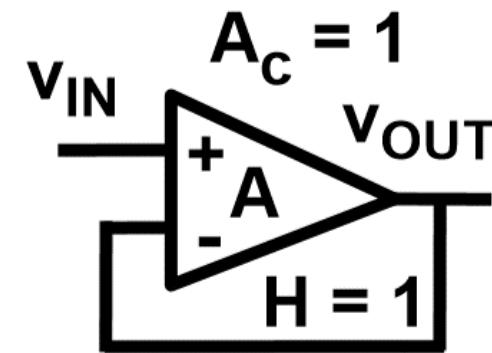
次极点刚好为增益带宽积

》》 两极点系统：推远非主极点



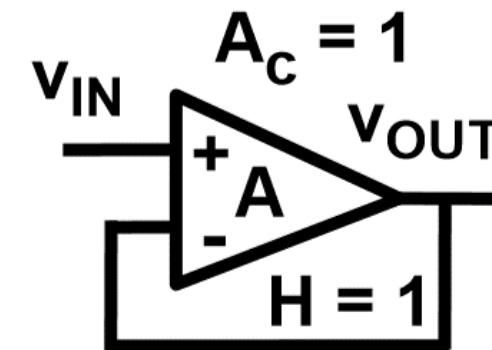
相位裕度的计算

$$\text{Open loop gain } A = \frac{A_o}{(1 + j \frac{f}{f_1})(1 + j \frac{f}{f_2})}$$



相位裕度的计算

$$\text{Open loop gain } A = \frac{A_o}{(1 + j \frac{f}{f_1})(1 + j \frac{f}{f_2})}$$



$$\begin{aligned}\text{Closed loop gain } A_c &= \frac{A}{1+A} \approx \frac{1}{1 + j \frac{f}{\text{GBW}} + j^2 \frac{f^2}{\text{GBW } f_2}} \\ &\approx \frac{1}{1 + j 2\zeta \frac{f}{f_r} + j^2 \frac{f^2}{f_r^2}}\end{aligned}$$

ζ is the damping ($=1/2Q$)

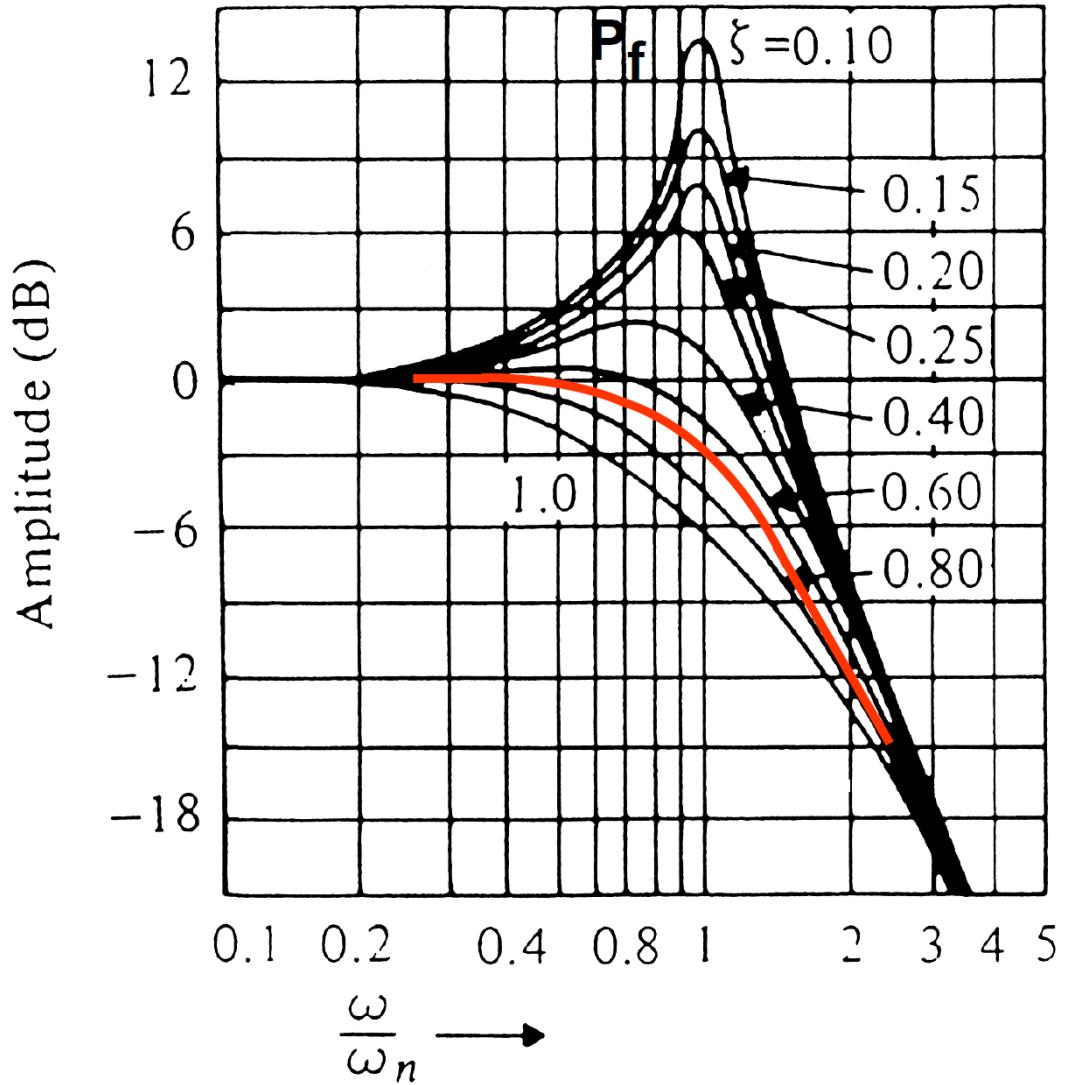
f_r is the resonant frequency

 相位裕度的计算

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

$\frac{f_2}{GBW}$	PM (°)	$\zeta = \frac{1}{2} \sqrt{\frac{f_2}{GBW}}$	P _f (dB)	P _t (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	0.71	0	0.37
3	72	0.87	0	0.04

》》 频域响应



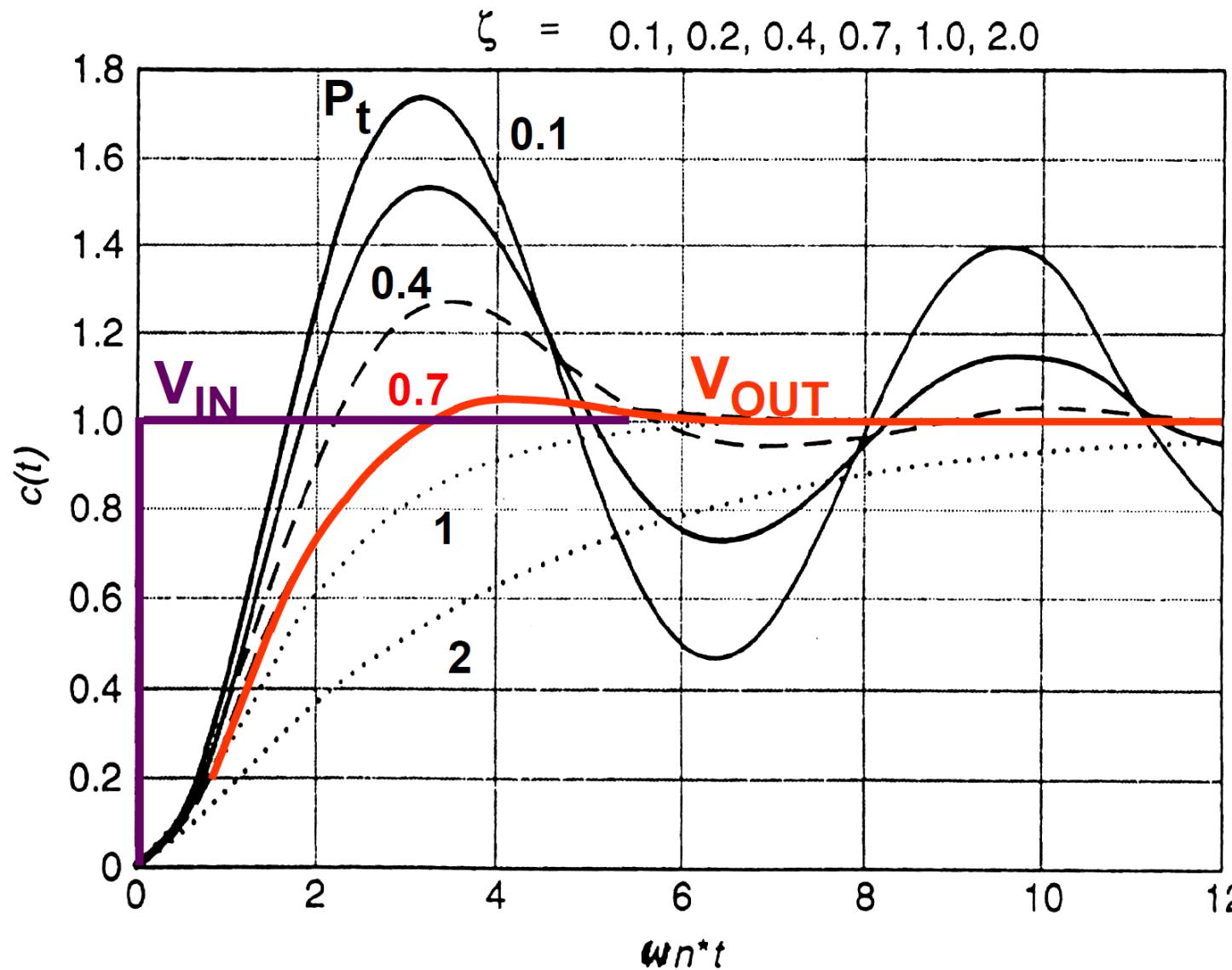
震荡

$\zeta = Q = 0.7$

带宽

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

时域响应



$$\zeta = Q = 0.7$$

$$P_t =$$

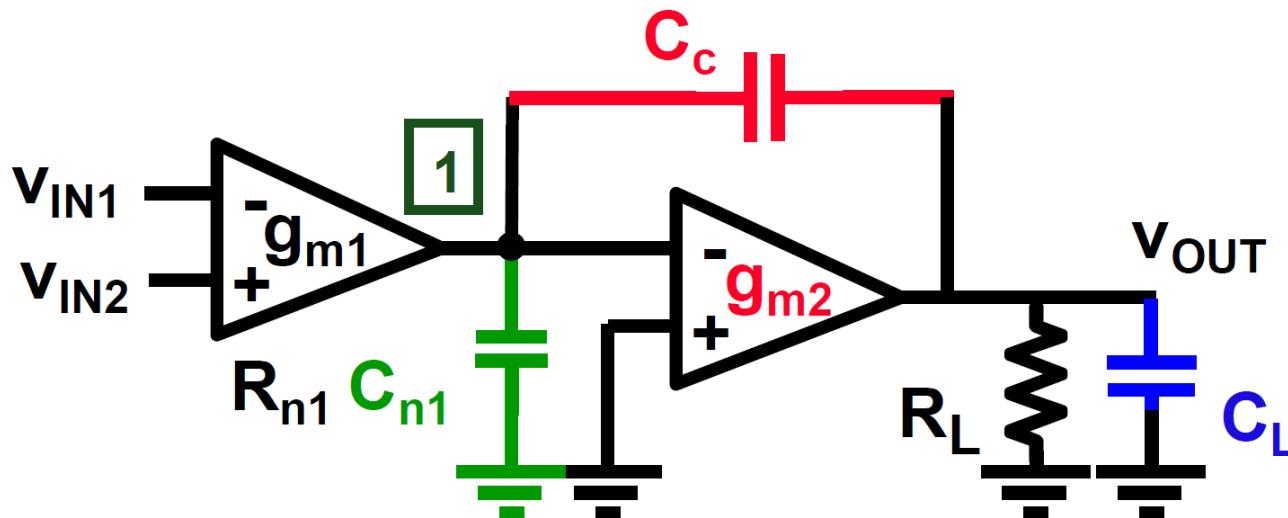
$$\frac{-\pi \zeta}{\sqrt{1 - \zeta^2}}$$



运放的稳定性与系统性设计

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» 标准两级运放



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

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

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

$$1 - \frac{C_c}{g_{m2}} s$$

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

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

》》 标准两级运放

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

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

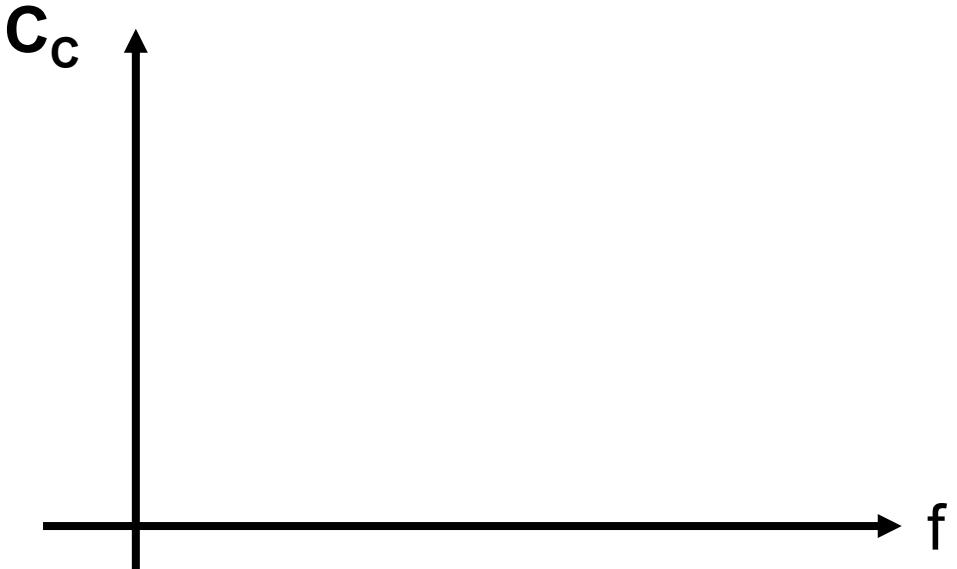
零点: $\frac{g_{m2}}{C_c}$

主极点: $-\frac{1}{R_{n1}C_{n1} + A_{v2}R_{n1}C_c + R_L C_L} \approx -\frac{1}{A_{v2}R_{n1}C_c}$

非主极点: $-\frac{R_{n1}C_{n1} + A_{v2}R_{n1}C_c + R_L C_L}{R_{n1}R_L C C} \approx \frac{g_{m2}}{C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$



极点分离技术：补偿电容Cc



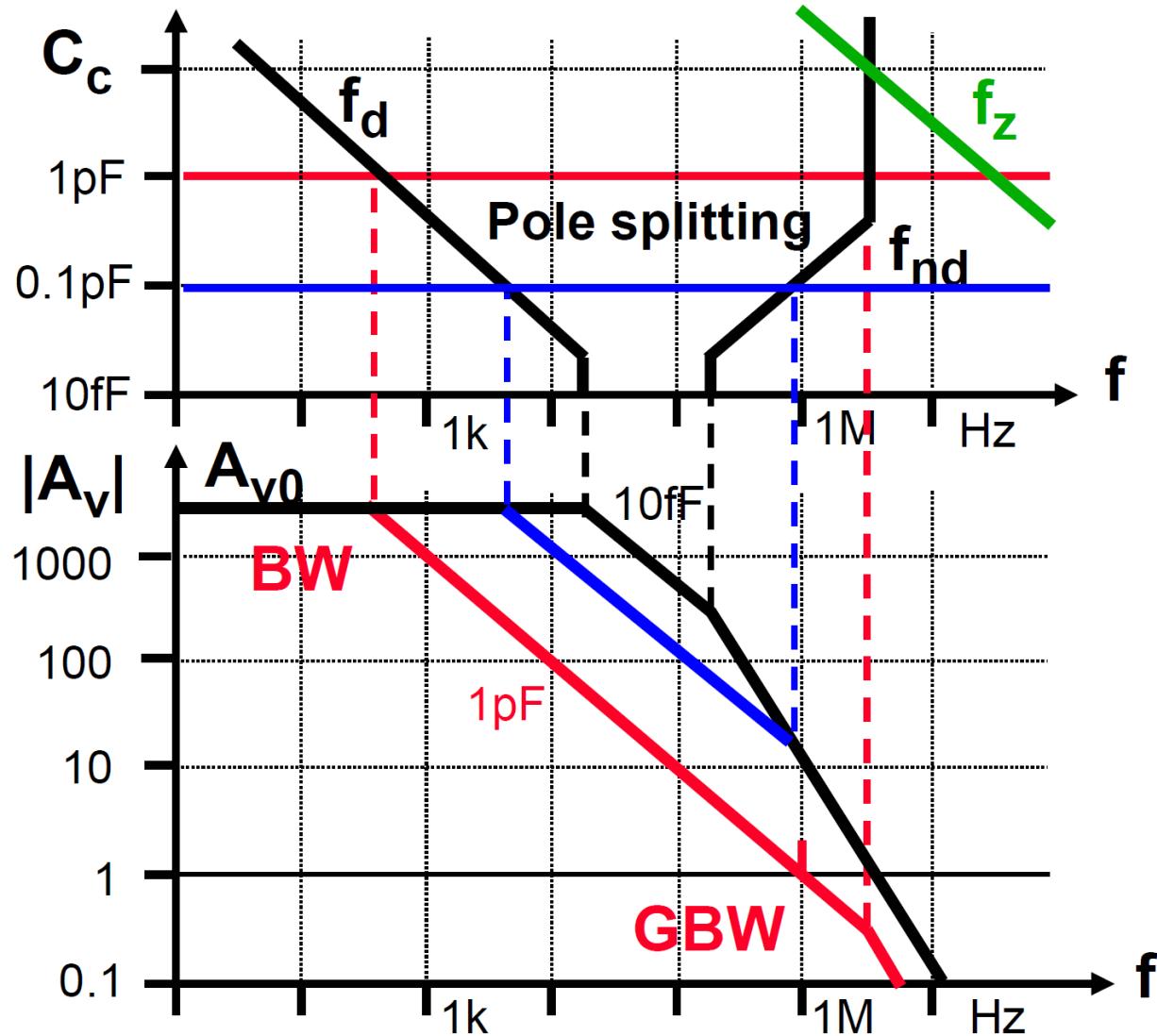
$$f_d = -\frac{1}{2\pi A_{v2} R_{n1} C_c}$$

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

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



极点分离技术：补偿电容Cc



$$f_d = -\frac{1}{2\pi A_{v2} R_{n1} C_c}$$

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

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

» 极点分离技术

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

$$f_{nd} = 3 \text{ GBW} = \frac{g_{m2}}{2\pi C_L} \cdot \frac{1}{1 + \frac{C_{n1}}{C_c}} \approx 0.3$$

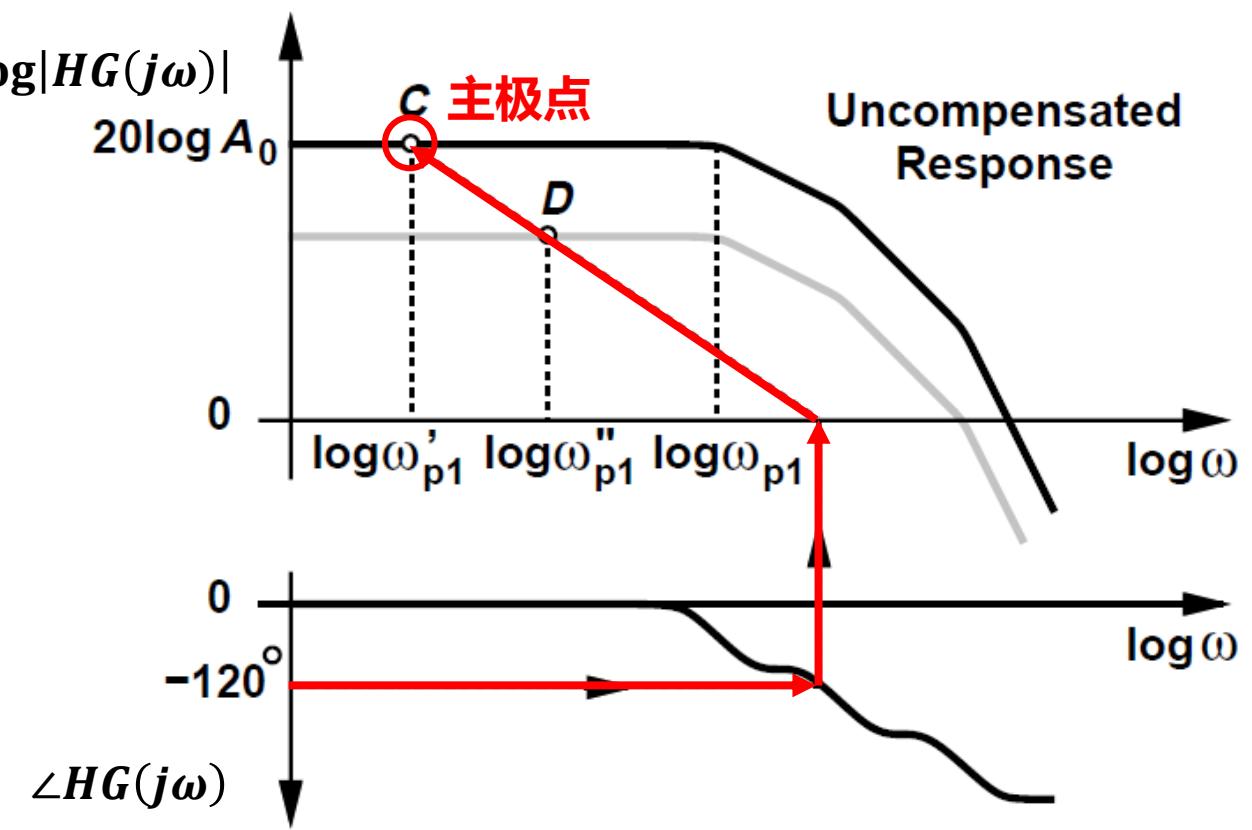
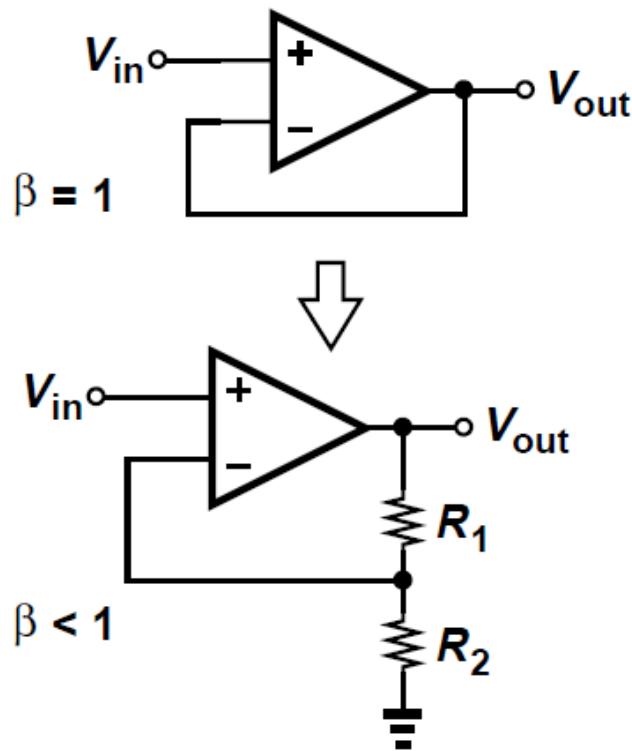
$$\frac{g_{m2}}{g_{m1}} \approx 4 \frac{C_L}{C_c}$$

Larger current in 2nd stage !

- 通常 C_c 至少是 C_{n1} 的 3 倍，结合 f_{nd} 需要是三倍的 GBW，得到 g_{m2} 和 g_{m1} 的比值为 4 倍关系

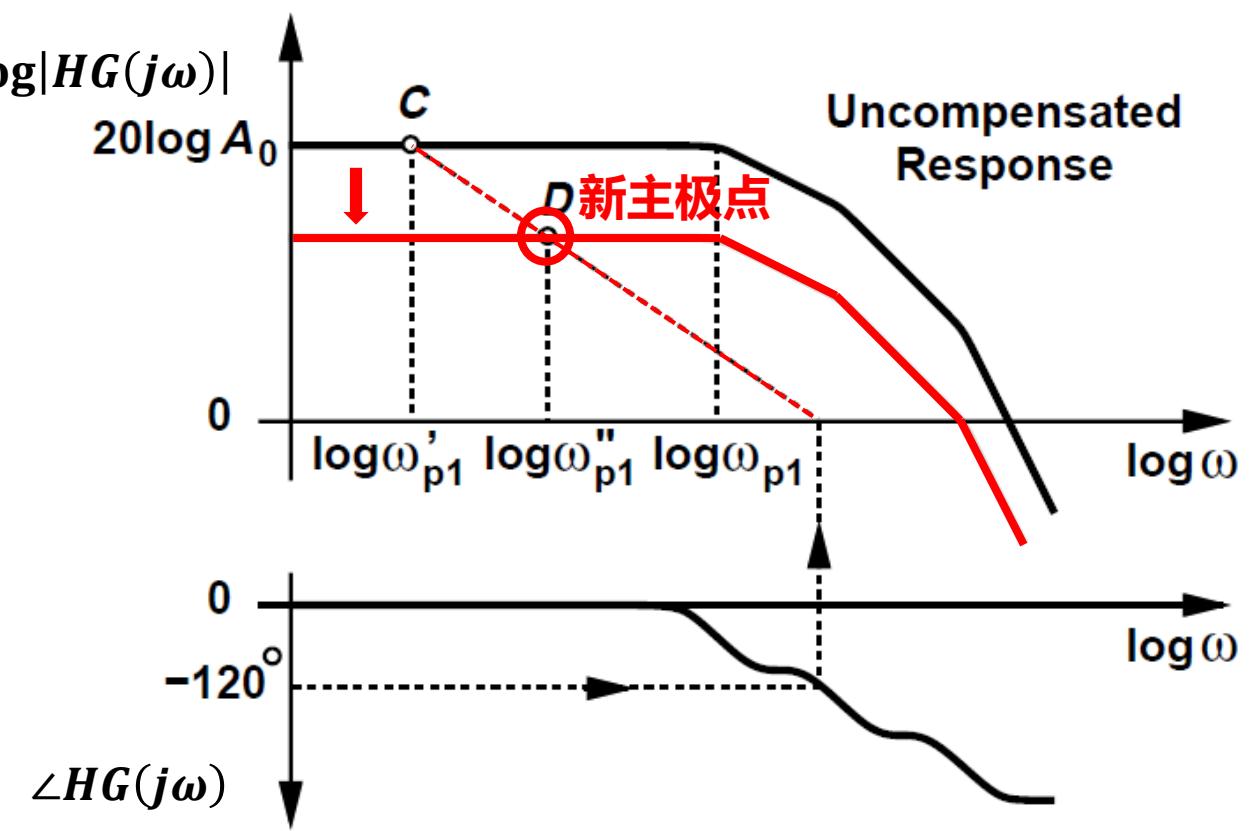
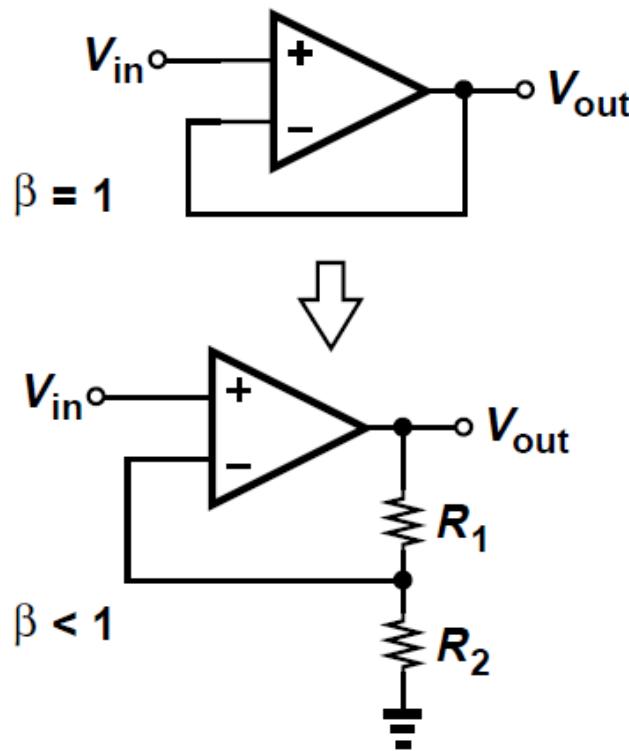
» 极点分离技术与反馈

□ 对于一两级放大器，其单位增益反馈稳定。如果电路以 $\beta < 1$ 的反馈系数运行，那么其主极点可以放宽多少？



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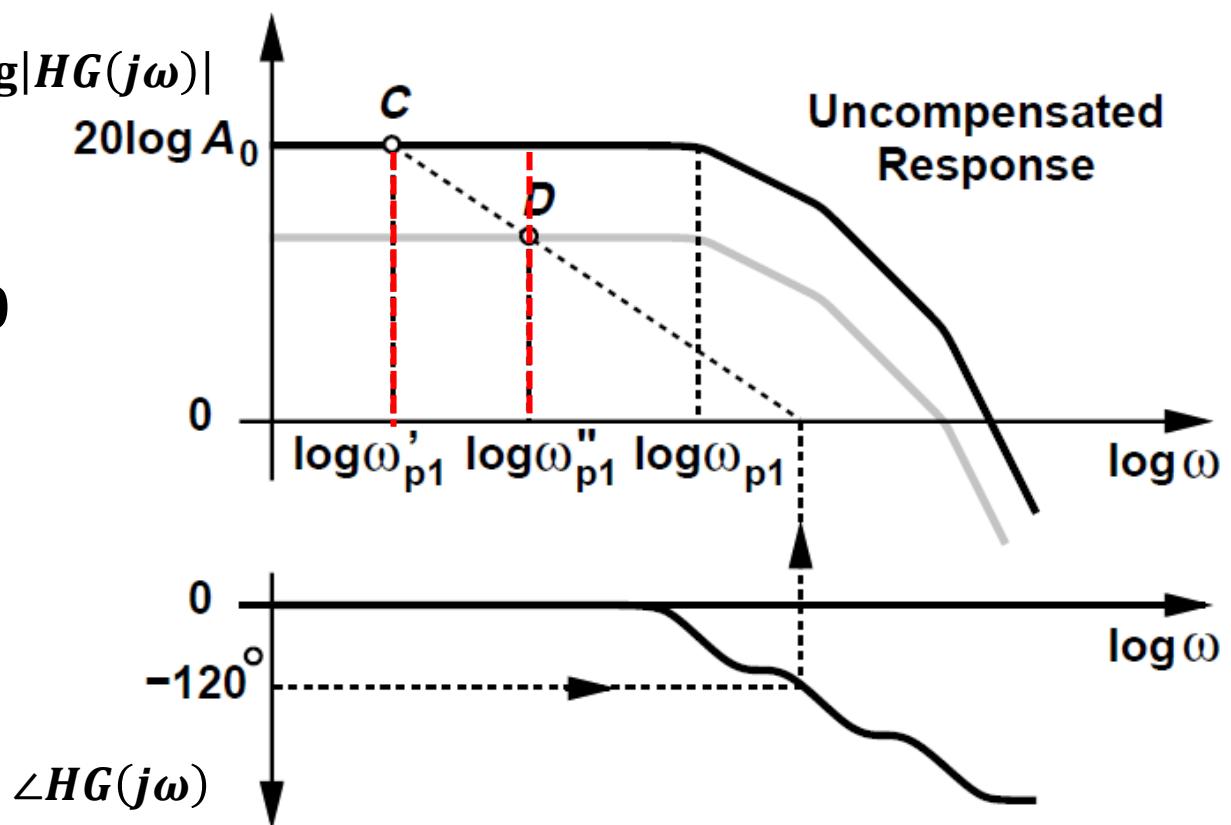
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$$\frac{20 \log A_0 - 20 \log(\beta A_0)}{\log \omega''_{p1} - \log \omega'_{p1}} = 20$$



$$\frac{\omega''_{p1}}{\omega'_{p1}} = \frac{1}{\beta}$$



» 稳定性与反馈



Low Power, $1 \text{ nV}/\sqrt{\text{Hz}}$, $G \geq 10$ Stable, Rail-to-Rail Output Amplifier

Data Sheet

ADA4895-1/ADA4895-2

FEATURES

Low wideband noise

$1 \text{ nV}/\sqrt{\text{Hz}}$

$1.6 \text{ pA}/\sqrt{\text{Hz}}$

Low $1/\text{f}$ noise: $2 \text{ nV}/\sqrt{\text{Hz}}$ at 10 Hz

Low distortion (SFDR): -96 dBc at 100 kHz , $V_{\text{OUT}} = 2 \text{ V p-p}$

Low power: 3 mA per amplifier

Low input offset voltage: $350 \mu\text{V}$ maximum

High speed

236 MHz , -3 dB bandwidth ($G = +10$)

$943 \text{ V}/\mu\text{s}$ slew rate

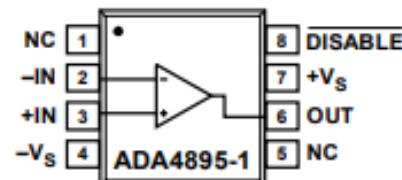
22 ns settling time to 0.1%

Rail-to-rail output

Wide supply range: 3 V to 10 V

Disable feature

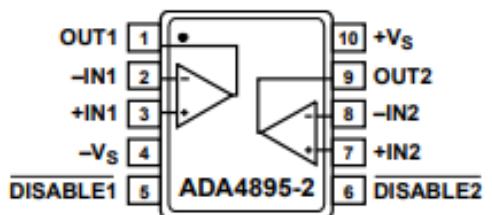
FUNCTIONAL BLOCK DIAGRAMS



NC = NO CONNECT. DO NOT CONNECT TO THIS PIN.

10186-102

Figure 1. ADA4895-1 Single Amplifier (8-Lead SOIC)



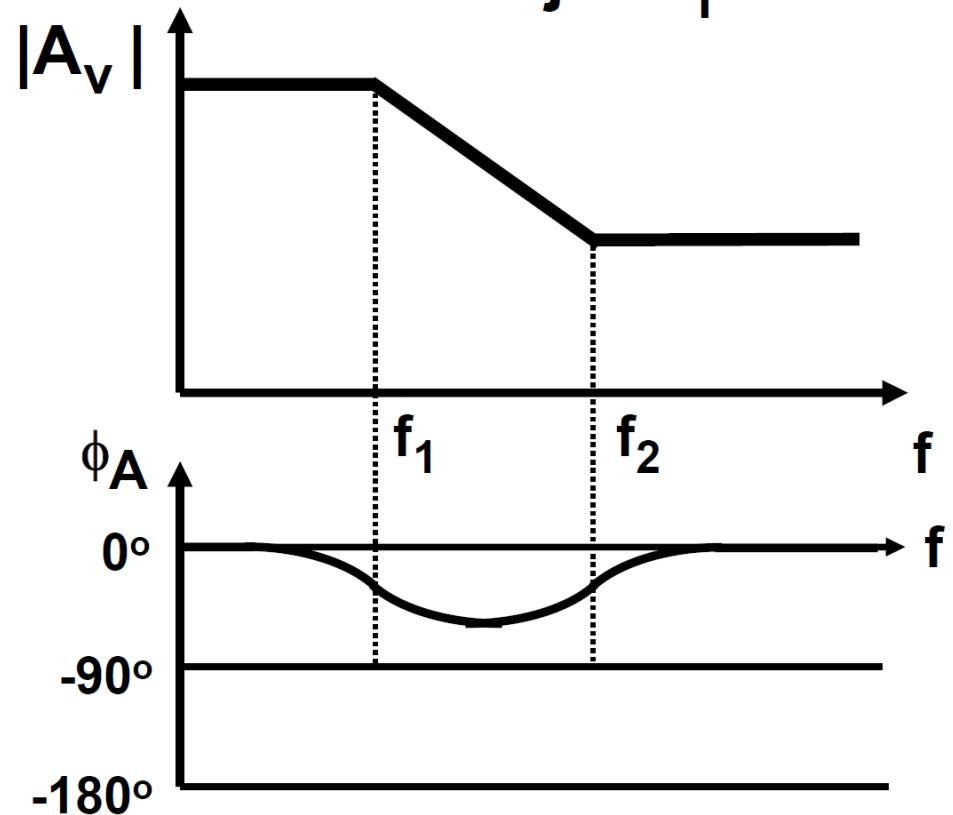
10186-001

Figure 2. ADA4895-2 Dual Amplifier (10-Lead MSOP)

正零点的作用

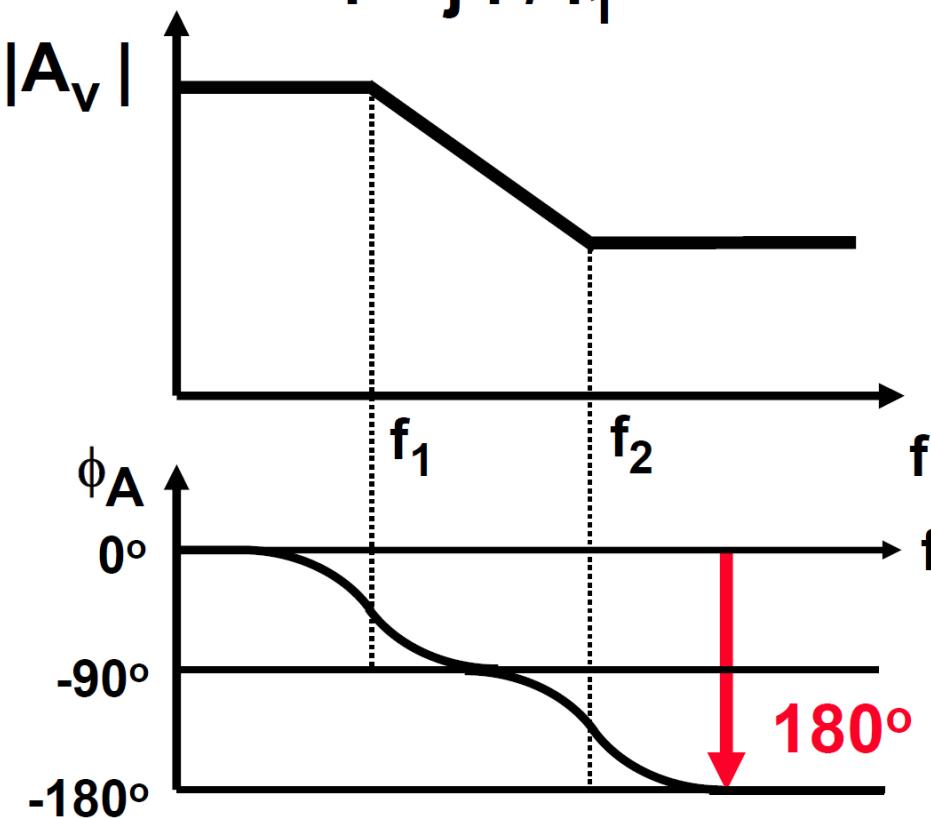
Negative zero

$$A_v = A_{v0} \frac{1 + j f / f_2}{1 + j f / f_1}$$



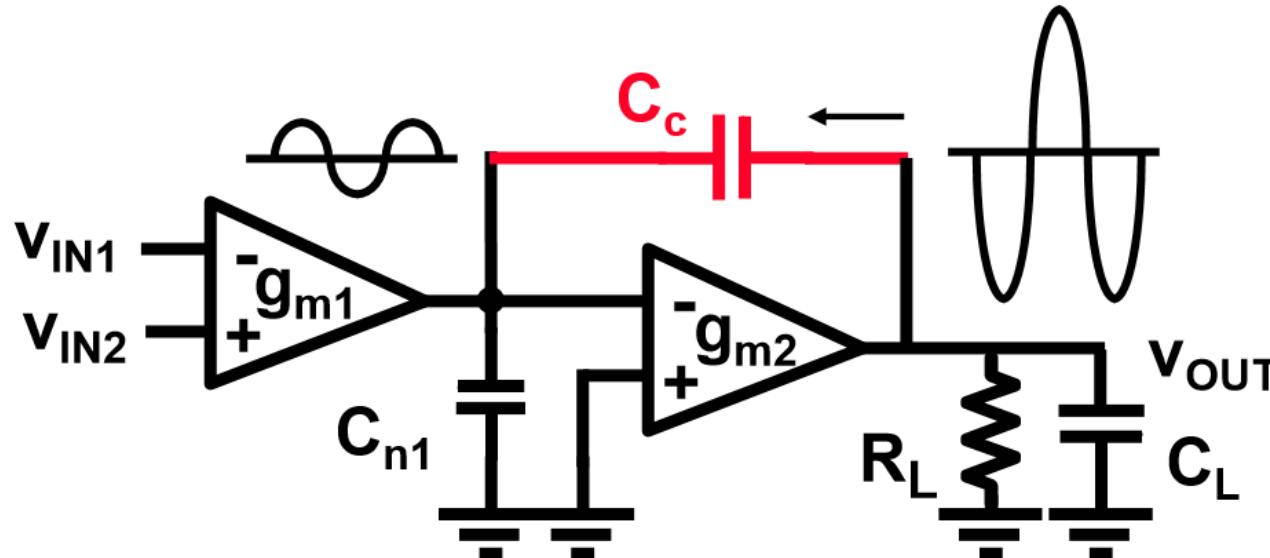
Positive zero

$$A_v = A_{v0} \frac{1 - j f / f_2}{1 + j f / f_1}$$

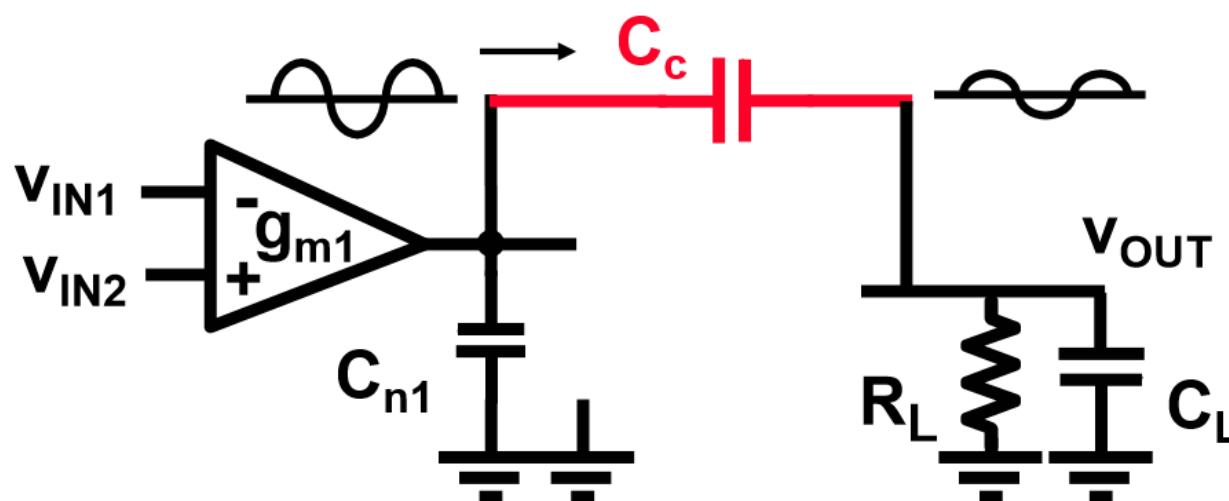


正零点和负极点的相位表现一样!

正零点补偿技术



米勒效应基于运放的反馈

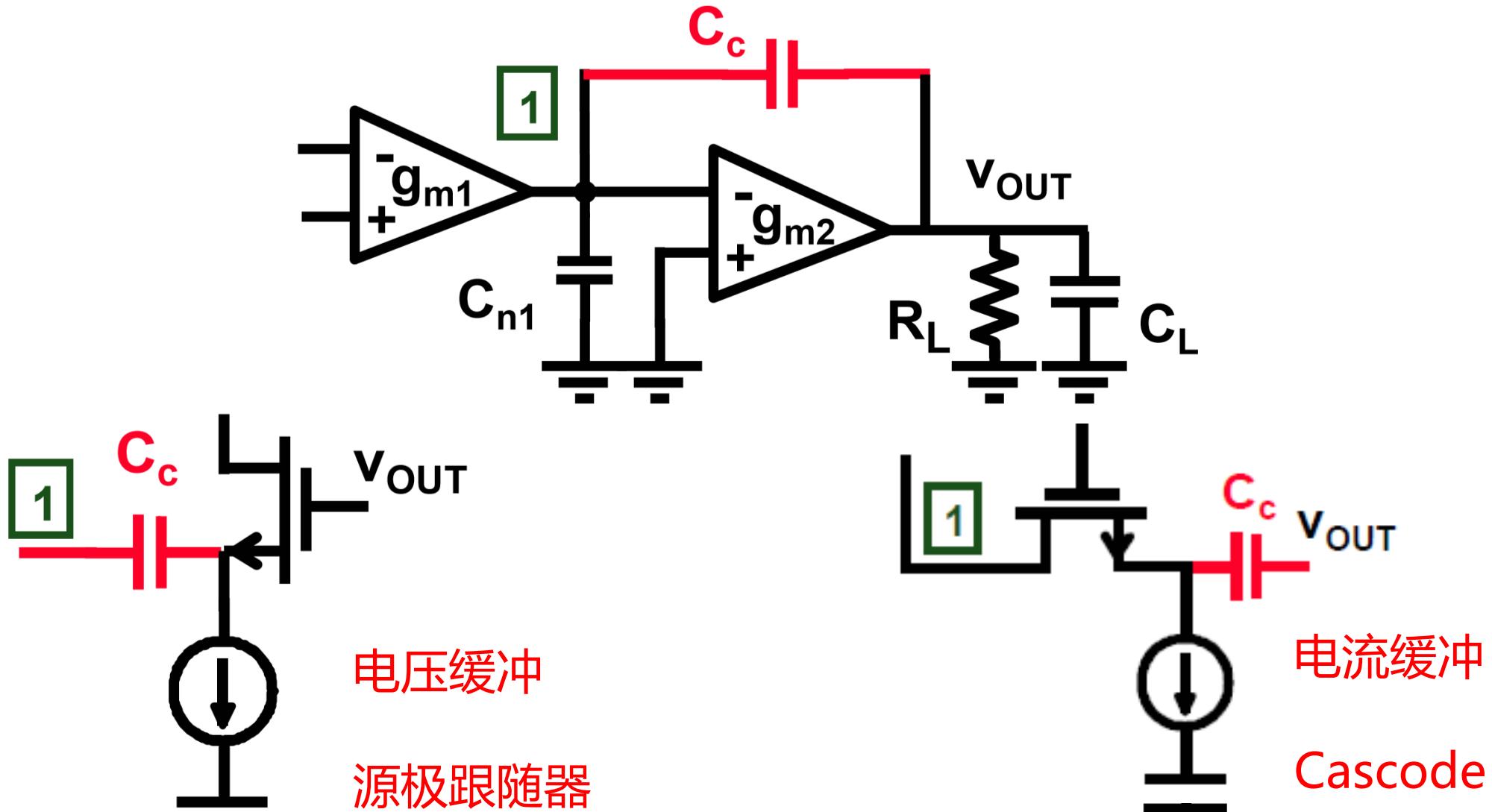


电容的前馈产生正的零点

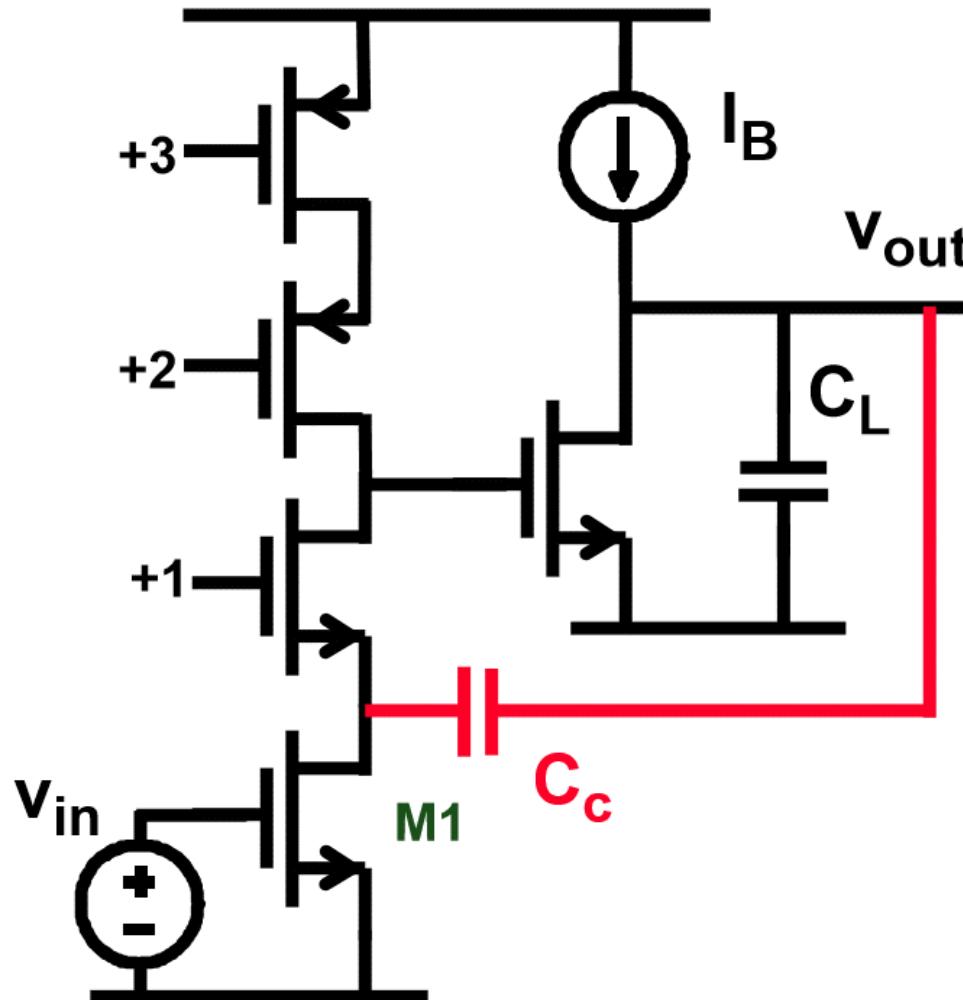
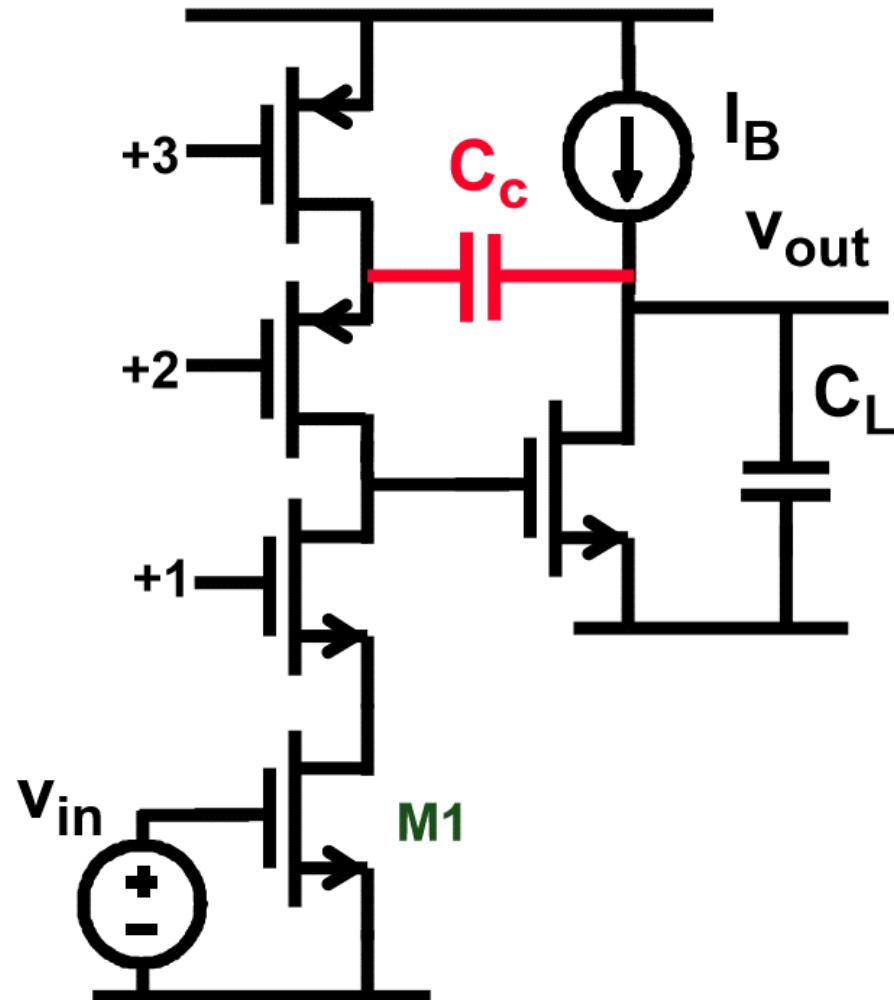
前馈的信号抵消反馈的信号

剪断前馈路径！

正零点补偿技术

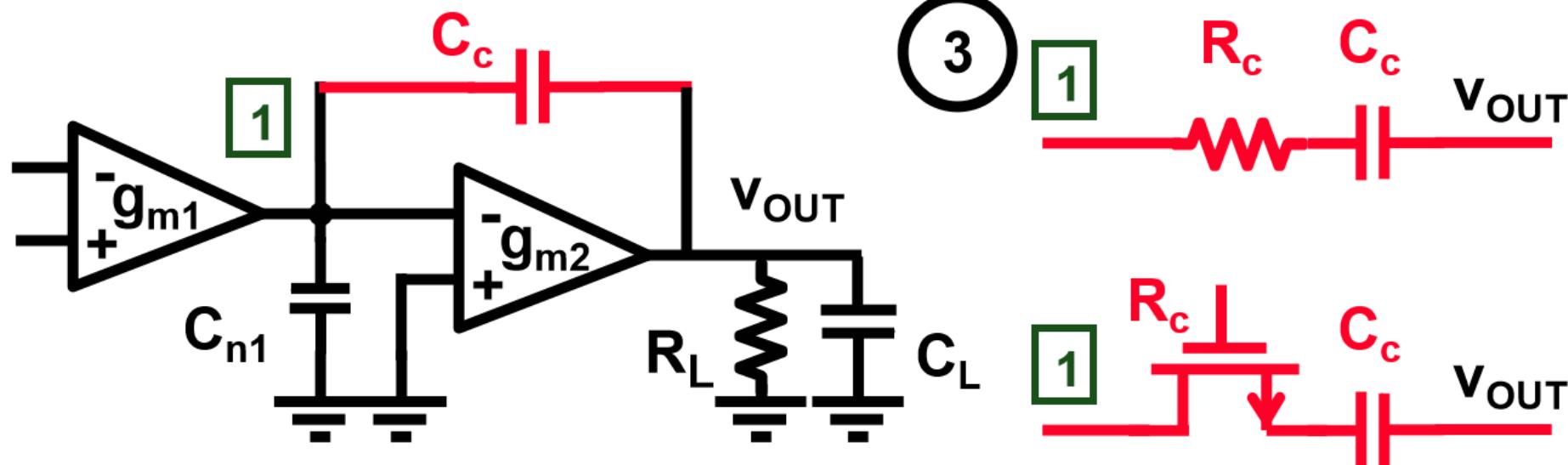


正零点补偿技术-Cascode

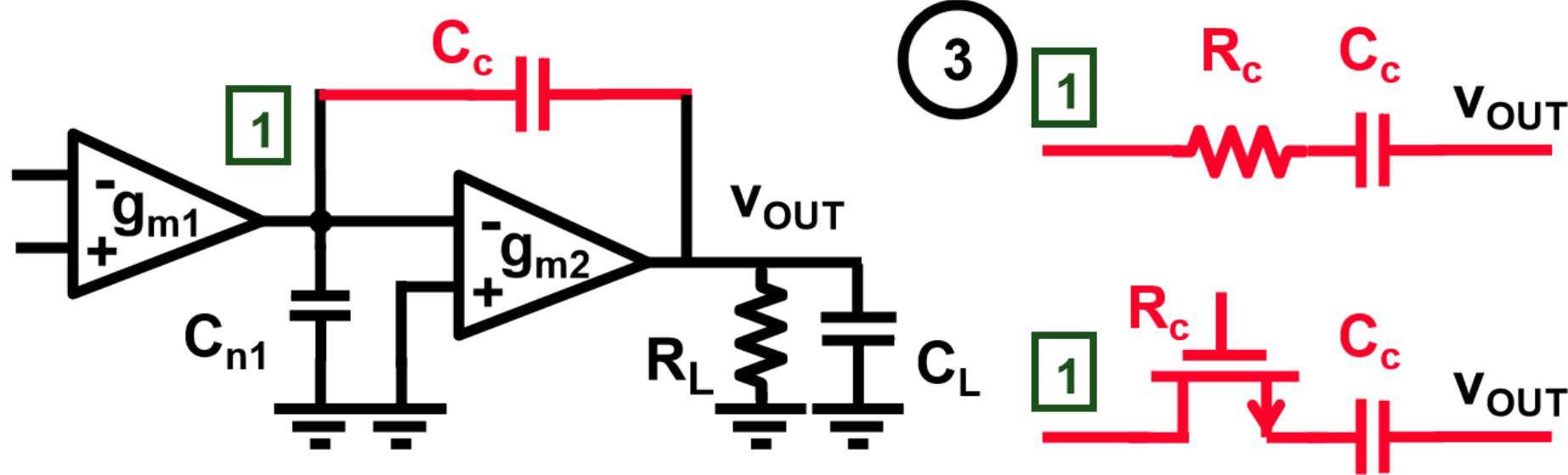


- Cascode级的使用没有额外的成本!

正零点补偿技术-串联电阻



正零点补偿技术-串联电阻



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

$R_c = 1/g_{m2}$ No zero

$R_c > 1/g_{m2}$ Negative zero

» 正零点补偿技术-串联电阻

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

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

Final choice :

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



随堂练习

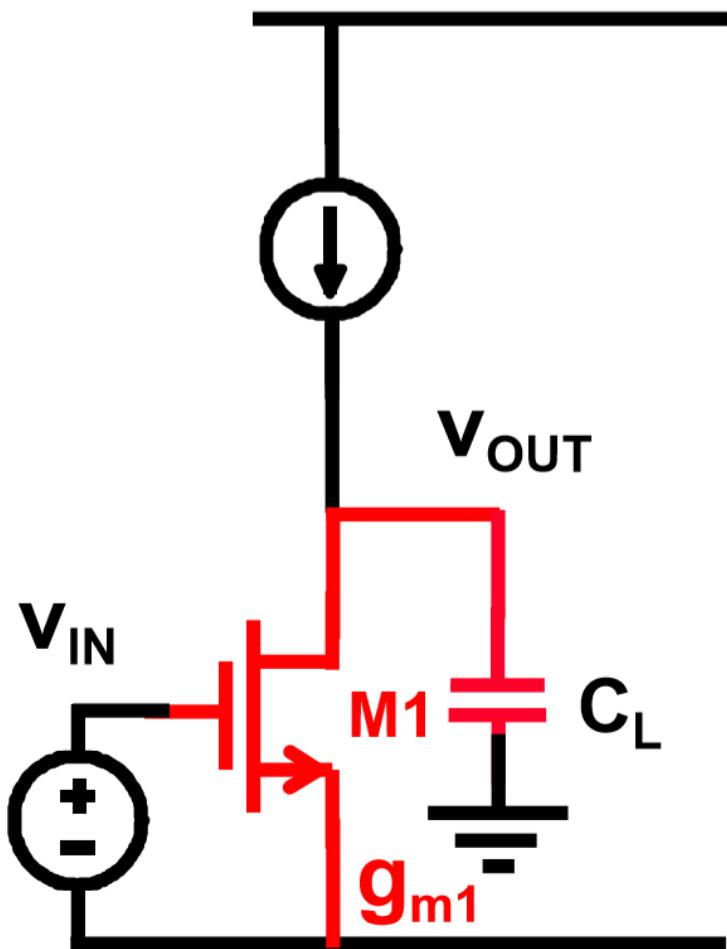
已知技术指标为 $GBW=100MHz$, 负载电容 $10pF$ 。对于一个米勒补偿的两级放大器, 给出一个第一级跨导 g_{m1} , 第二级跨导 g_{m2} 和补偿电容 C_c 的组合。



运放的稳定性与系统性设计

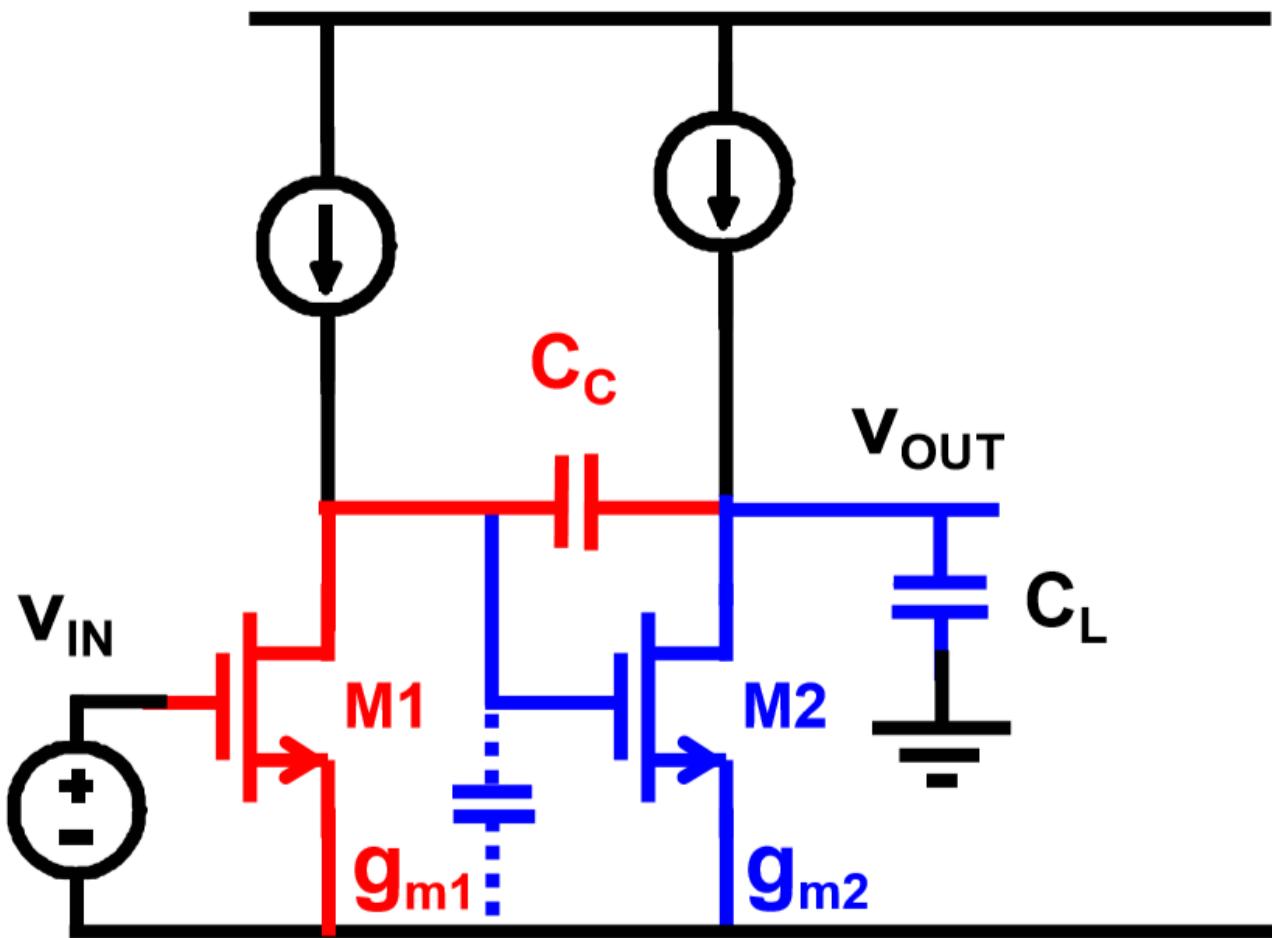
- 运放、反馈与稳定性的基本概念
- 极点分离与零点补偿
- **三级运放稳定性问题简介**
- 运放的系统性设计方法
- 运放的其他参数指标

» 三级运放的稳定性



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

» 三级运放的稳定性

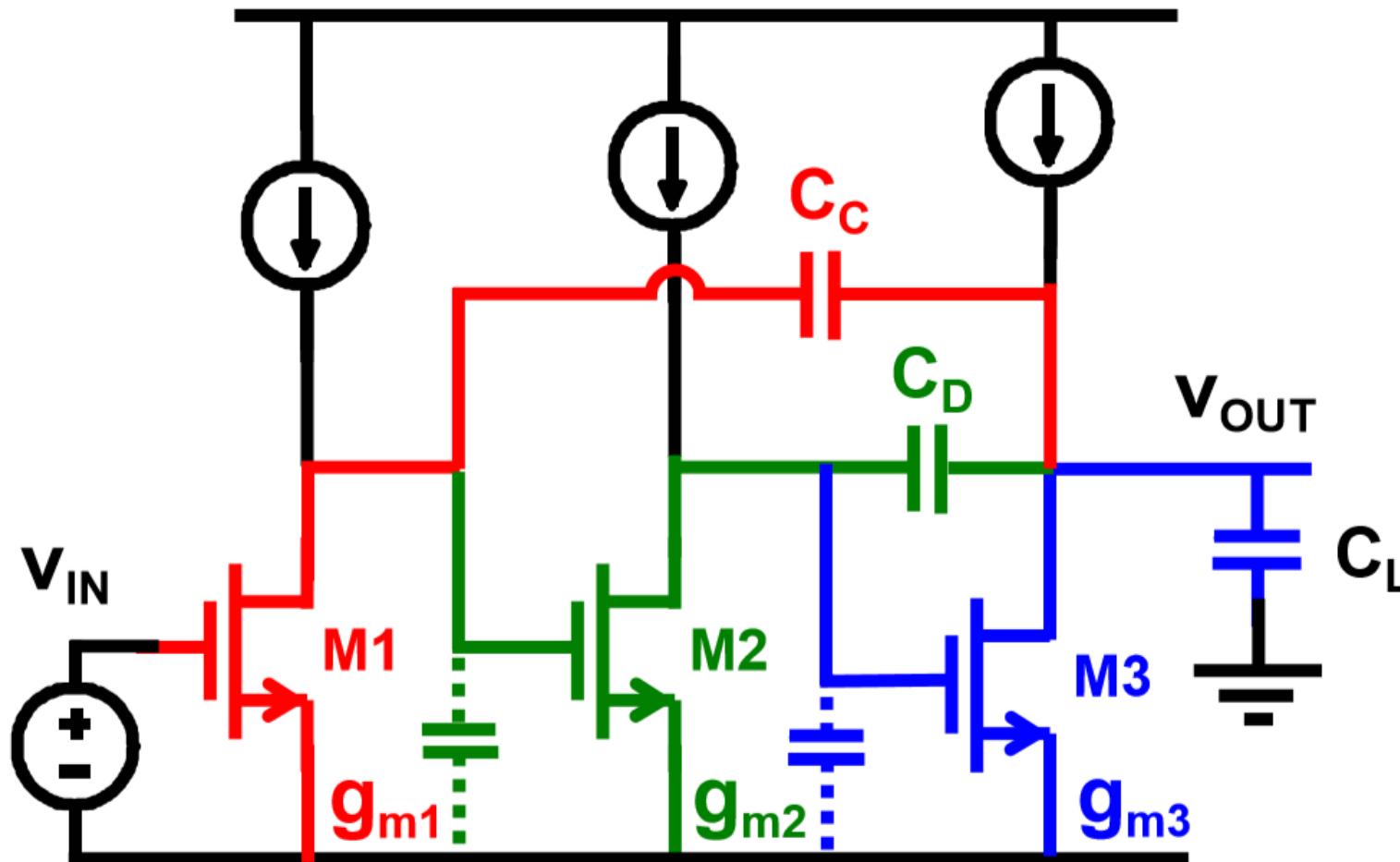


$$GBW = \frac{g_{m1}}{2\pi C_C}$$

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

$$f_{nd1} = 3 GBW$$

» 三级运放的稳定性



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

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

$$f_{nd2} = \frac{g_{m3}}{2\pi C_L}$$

$$f_{nd1} = 3 \text{ GBW}$$

$$f_{nd2} = 5 \text{ GBW}$$

»» 三级运放的稳定性

$$\text{GBW} = \frac{g_{m1}}{2\pi C_C}$$

$$f_{nd1} = 3 \text{ GBW} = \frac{g_{m2}}{2\pi C_D}$$

$$f_{nd2} = 5 \text{ GBW} = \frac{g_{m3}}{2\pi C_L}$$

Choose $C_D \approx C_C$!

$$\frac{g_{m2}}{g_{m1}} \approx 3$$

$$\frac{g_{m3}}{g_{m1}} \approx 5 \frac{C_L}{C_C}$$

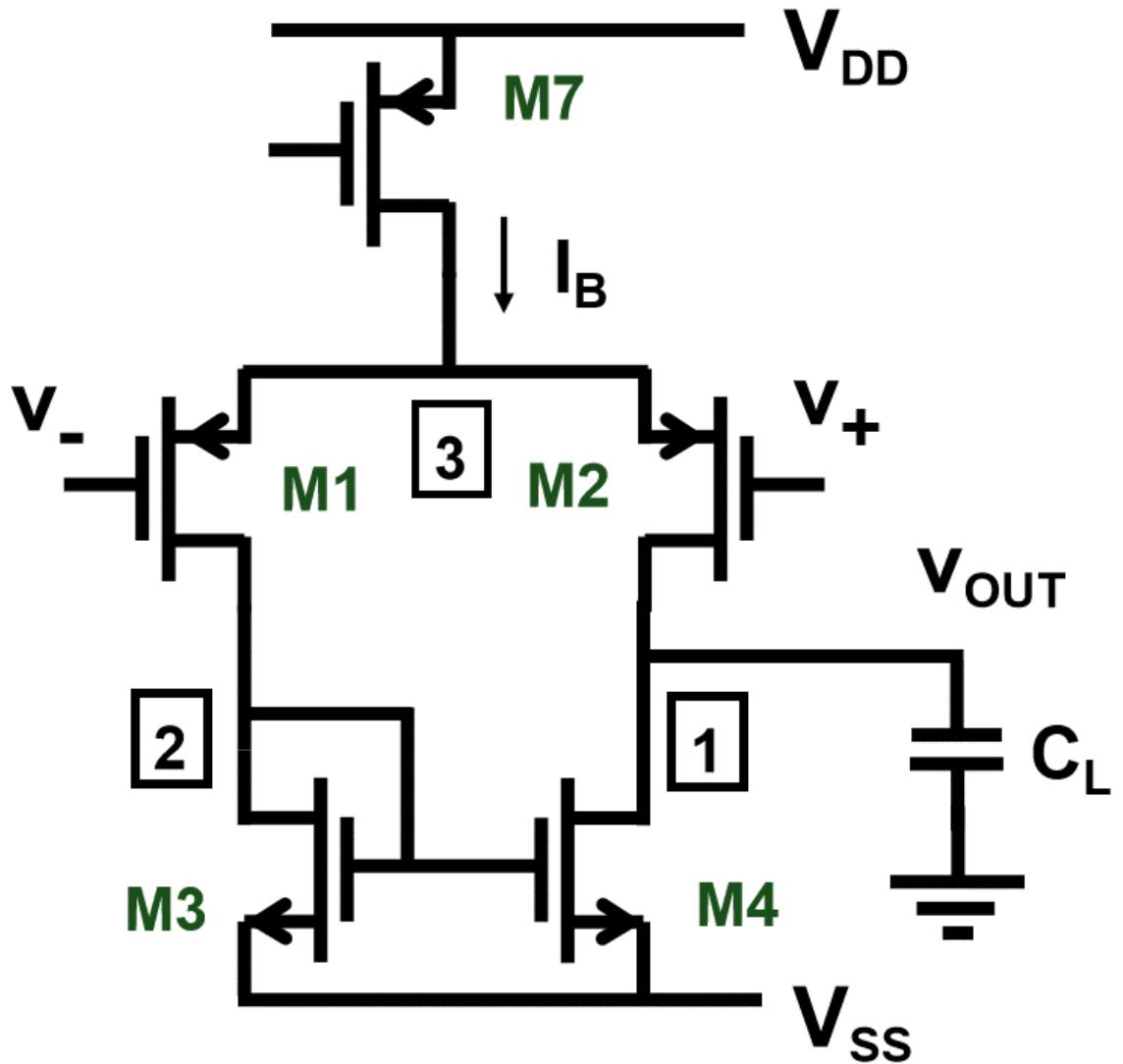
输出级更大的电流需求！



运放的稳定性与系统性设计

- 运放、反馈与稳定性的基本概念
- 极点分离与零点补偿
- 三级运放稳定性问题简介
- **运放的系统性设计方法**
- 运放的其他参数指标

» 一级OTA的设计



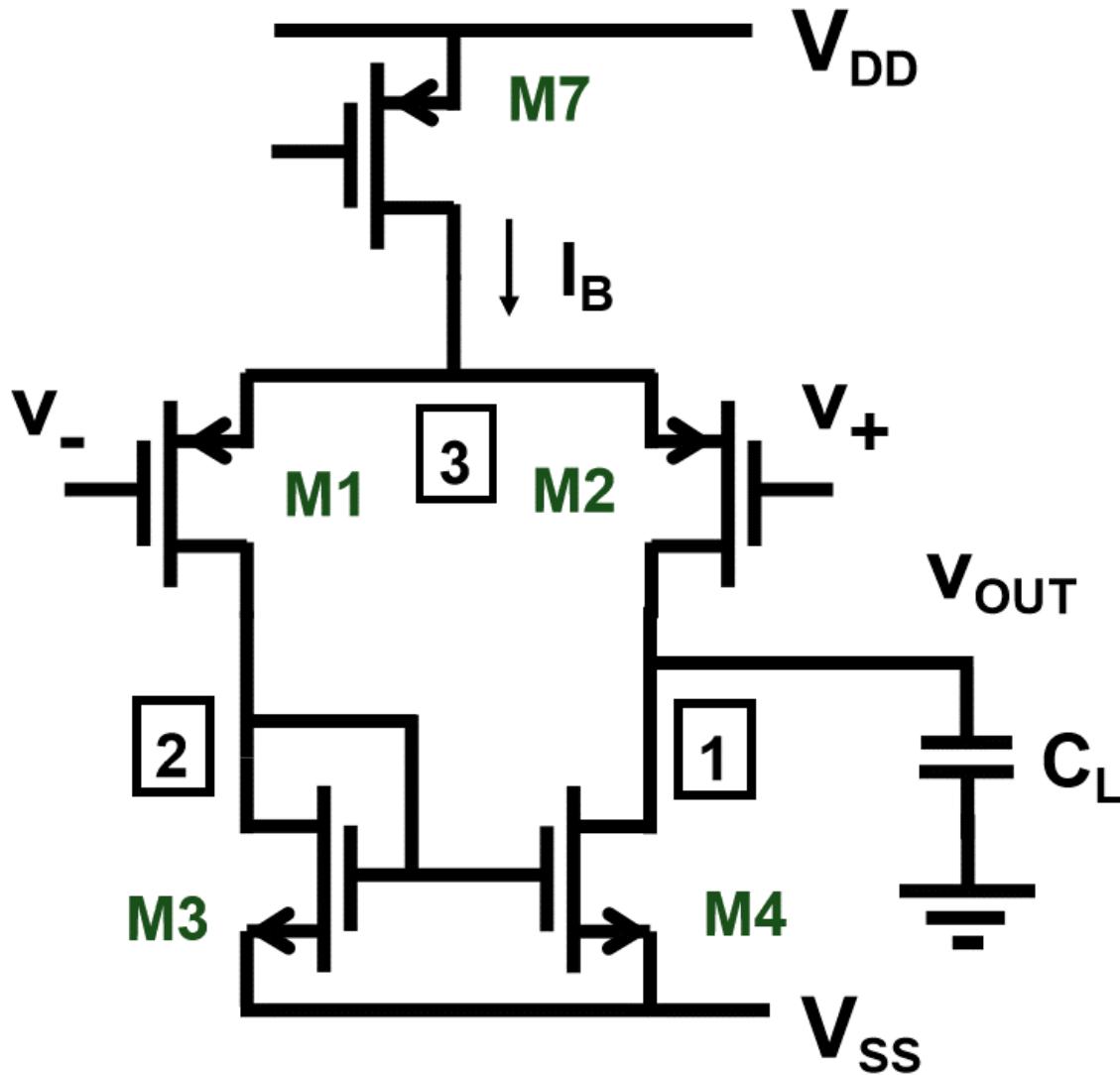
$$A_v =$$

$$BW =$$

$$GBW =$$

- GBW的最大值?
- 如何衡量运放的性能?

» 一级OTA的设计



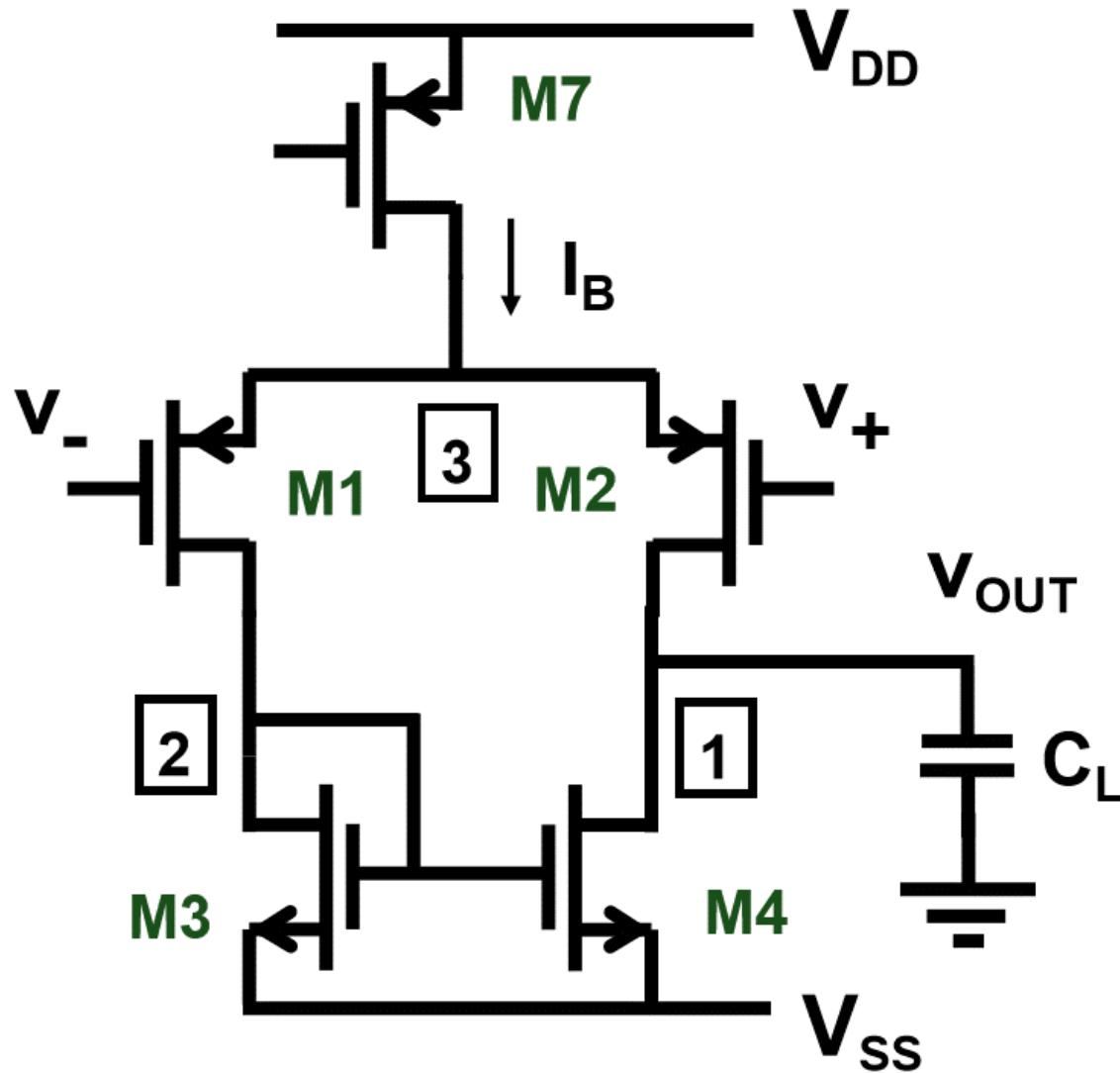
$$A_v = g_{m1} \frac{r_o}{2}$$

if $r_{o2} = r_{o4} = r_o$

$$BW = \frac{1}{2\pi \frac{r_o}{2} (C_L + C_{n1})}$$

$$GBW = \frac{g_{m1}}{2\pi (C_L + C_{n1})}$$

» 一级OTA的设计



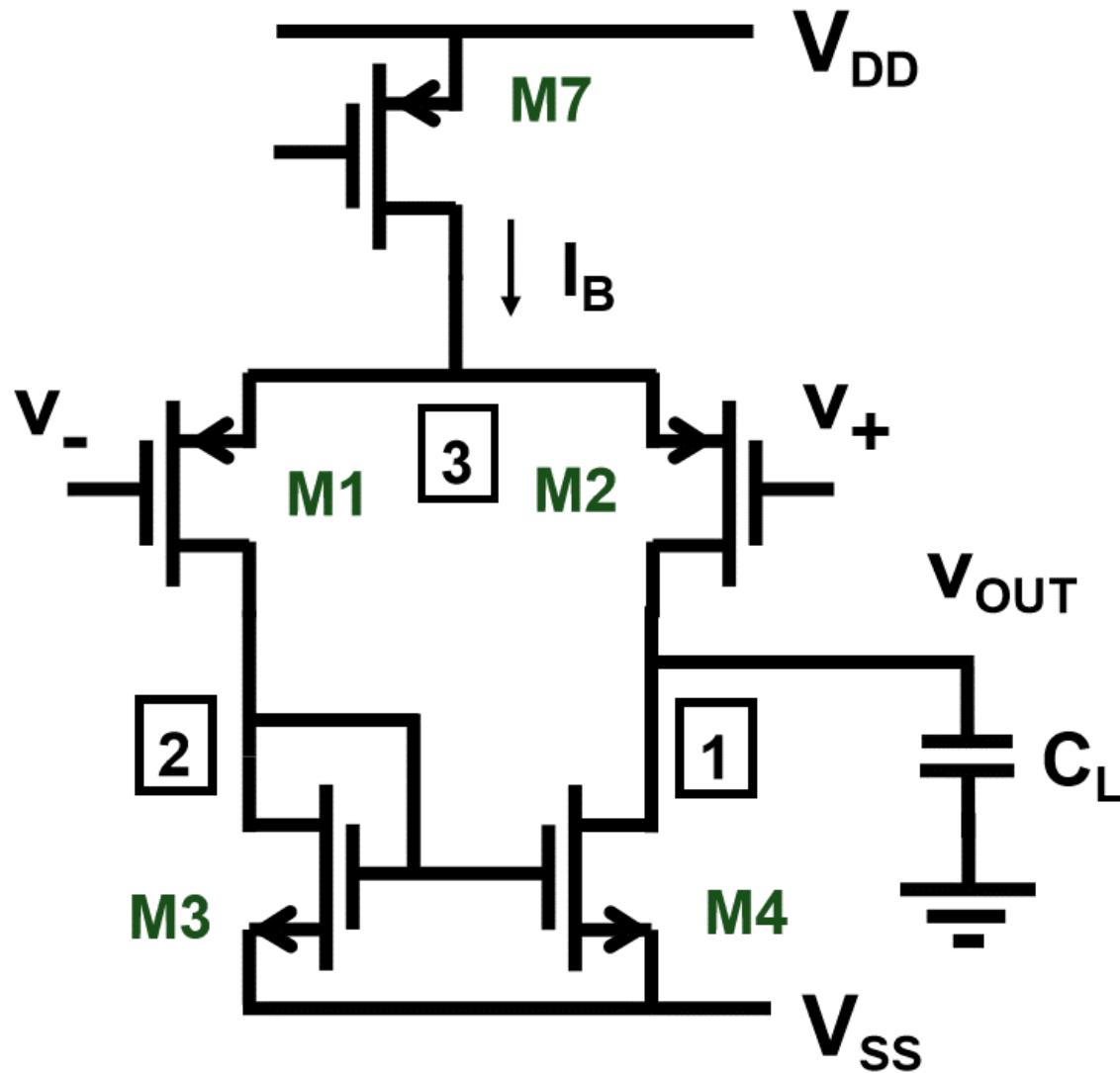
定义品质因素
Figure of Merit (FOM)

$$FOM = \frac{GBW \cdot C_L}{I_B}$$

□ 假设 $I_B=200\mu A$, $C_L=4pF$, C_{n1} 忽略不计, 求一阶OTA的FOM?

$$FOM \approx 800MHz \cdot pF/mA$$

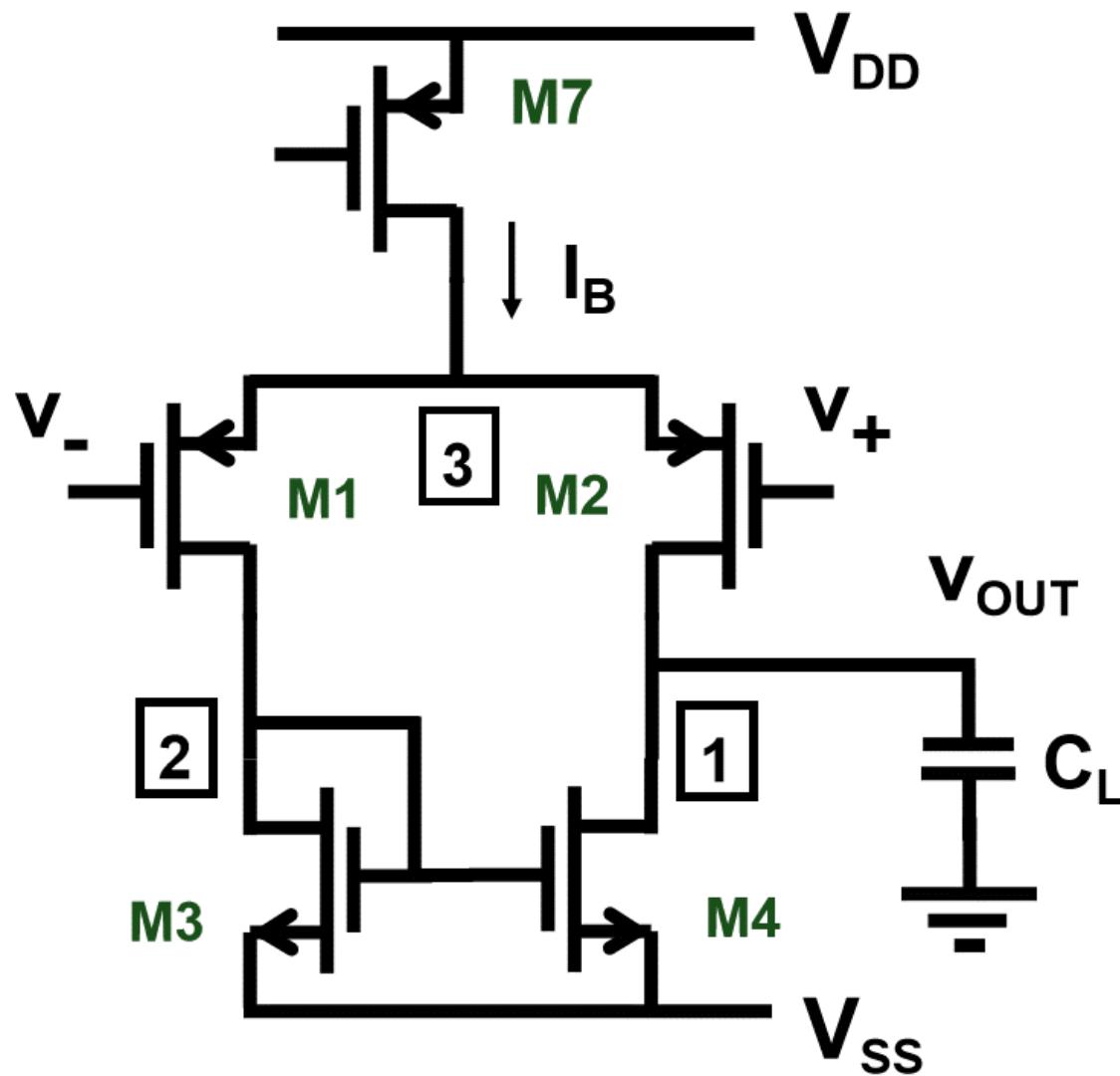
» 一级OTA的设计: f_{nd}



$$f_{nd} =$$

- 该电路的寄生电容是否会产生非主极点？在哪里？
- 是否会使得该一阶OTA不稳定？

» 一级OTA的设计: f_{nd}



$$GBW = \frac{g_{m1}}{2\pi (C_L + C_{n1})}$$

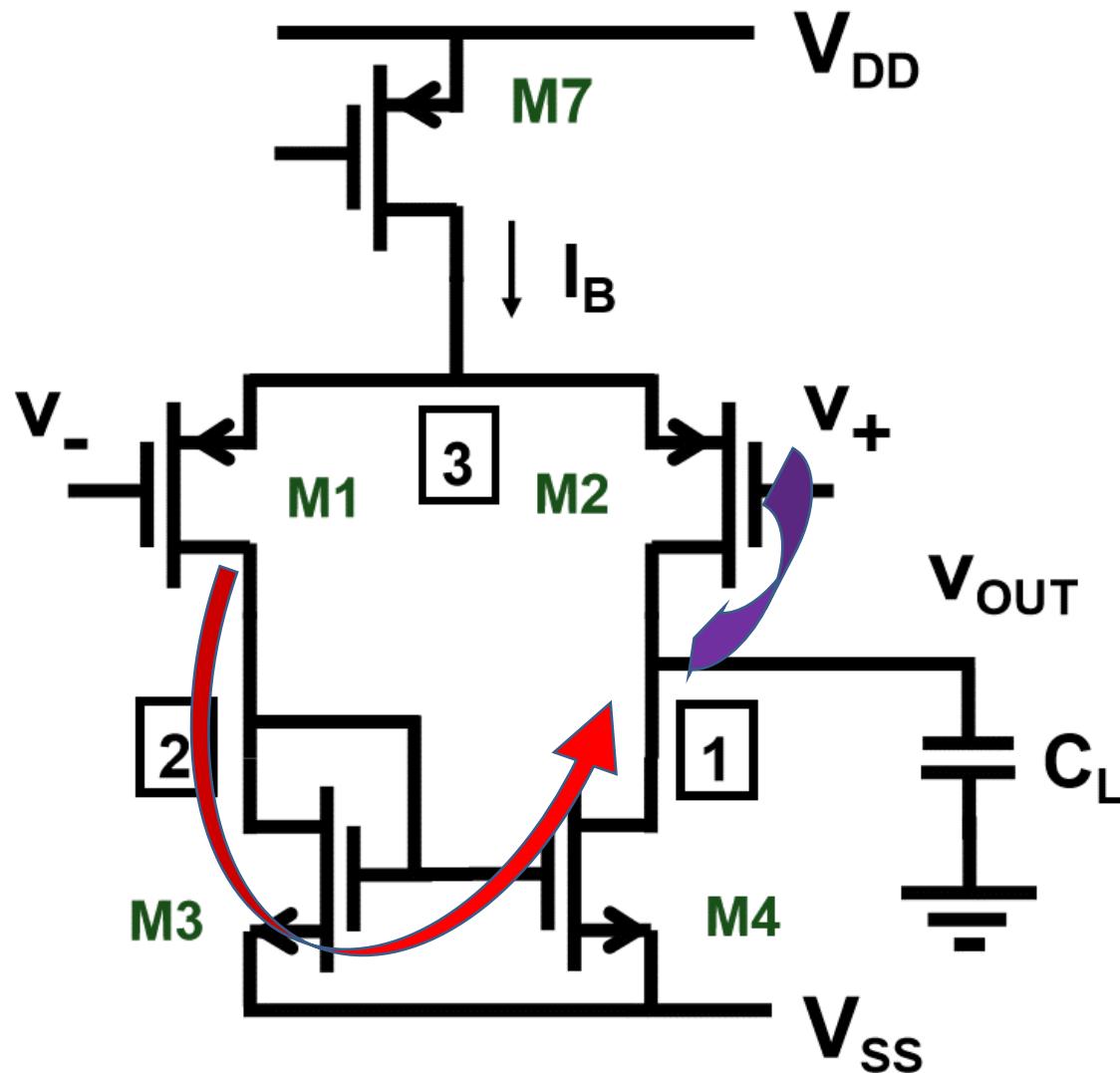
$$f_{nd} = \frac{g_{m3}}{2\pi C_{n2}}$$

$$\begin{aligned} C_{n2} &\approx 2C_{GS3} + C_{DB3} + C_{DB1} \\ &\approx 4 C_{GS3} \end{aligned}$$

$$f_{nd} \approx \frac{f_{T3}}{4}$$

✓ Net2 处非主极点
离主极点较远

» 极点-零点对 (pole-zero doublet)



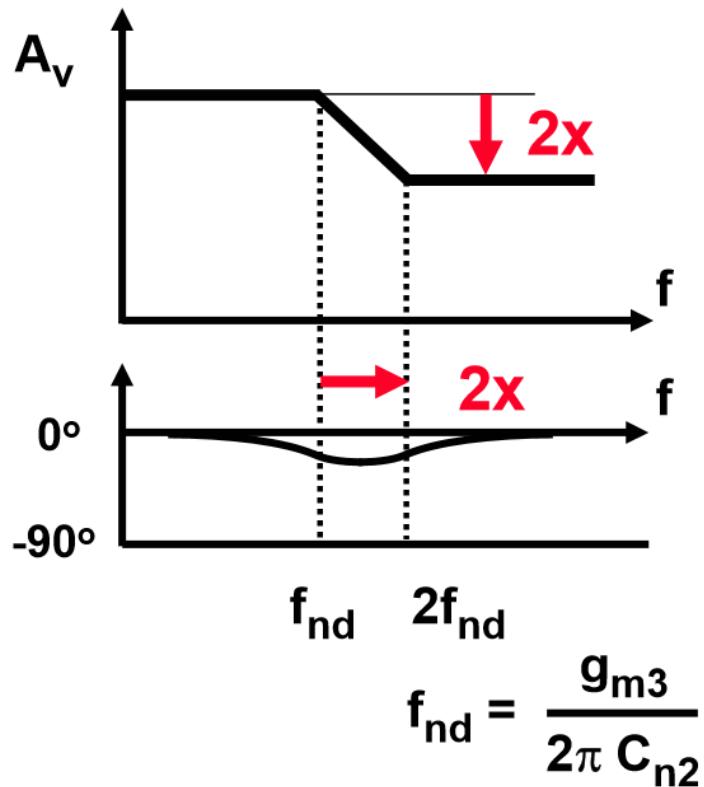
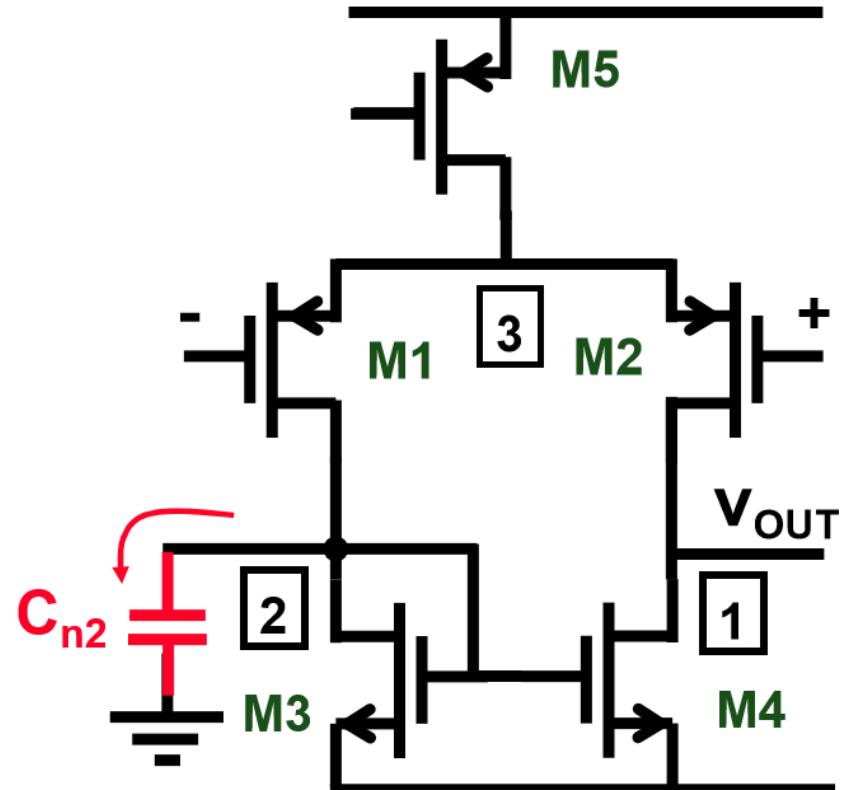
✓ Net2 的寄生电容同时会产生一个零点

$$H_f(s) = \frac{A_0}{1 + s/\omega_{p1}}$$

$$H_s(s) = \frac{A_0}{(1 + \frac{s}{\omega_{p1}})(1 + \frac{s}{\omega_{p2}})}$$

$$H_{f+s}(s) = \frac{A_0(2 + \frac{s}{\omega_{p2}})}{(1 + \frac{s}{\omega_{p1}})(1 + \frac{s}{\omega_{p2}})}$$

» 极点-零点对 (pole-zero doublet)



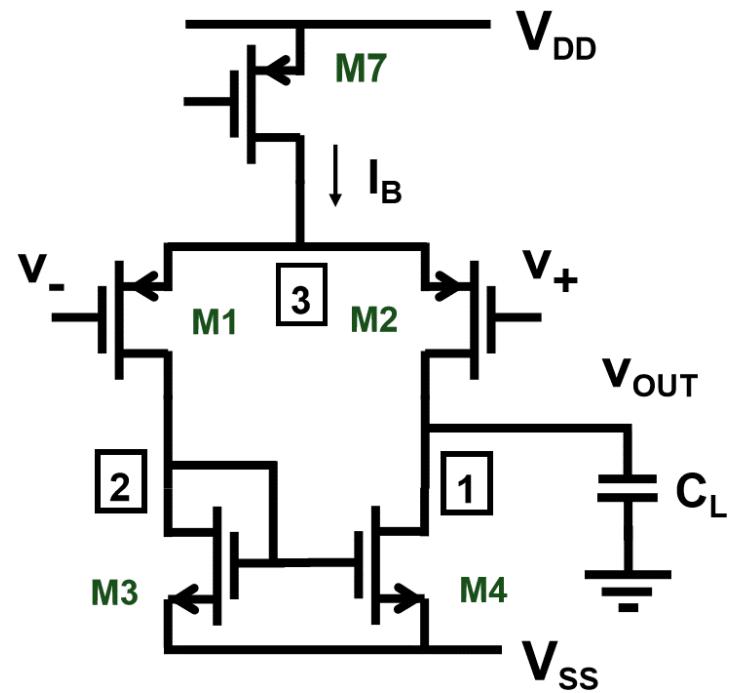
$$PM = 90^\circ - \arctan \frac{GBW}{f_{nd}} + \arctan \frac{GBW}{2f_{nd}} \approx 85^\circ$$

- 高频时，增益减半
- 虽然在频域上产生的作用忽略不计，但是在时域上会对稳定时间产生较大影响

» 一级OTA的设计

□按要求设计OTA中晶体管尺寸。要求GBW=100MHz, $C_L=2\text{pF}$ 。

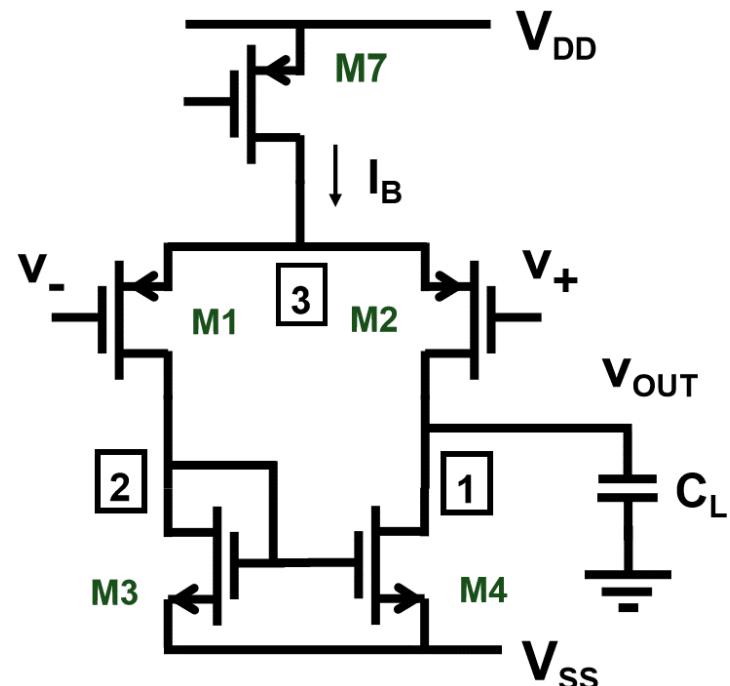
已知工艺参数为: $L_{min}=0.18\mu\text{m}$, $KP_n' = 280\text{uA/V}^2$, $KP_p' = 70\text{uA/V}^2$



» 一级OTA的设计

□按要求设计OTA中晶体管尺寸。要求 $GBW=100MHz$, $C_L=2pF$ 。

已知工艺参数为: $L_{min}=0.18\mu m$, $KP_n' = 280\mu A/V^2$, $KP_p' = 70\mu A/V^2$



$$g_m = GBW \cdot 2\pi C_L = 1.256mA/V$$

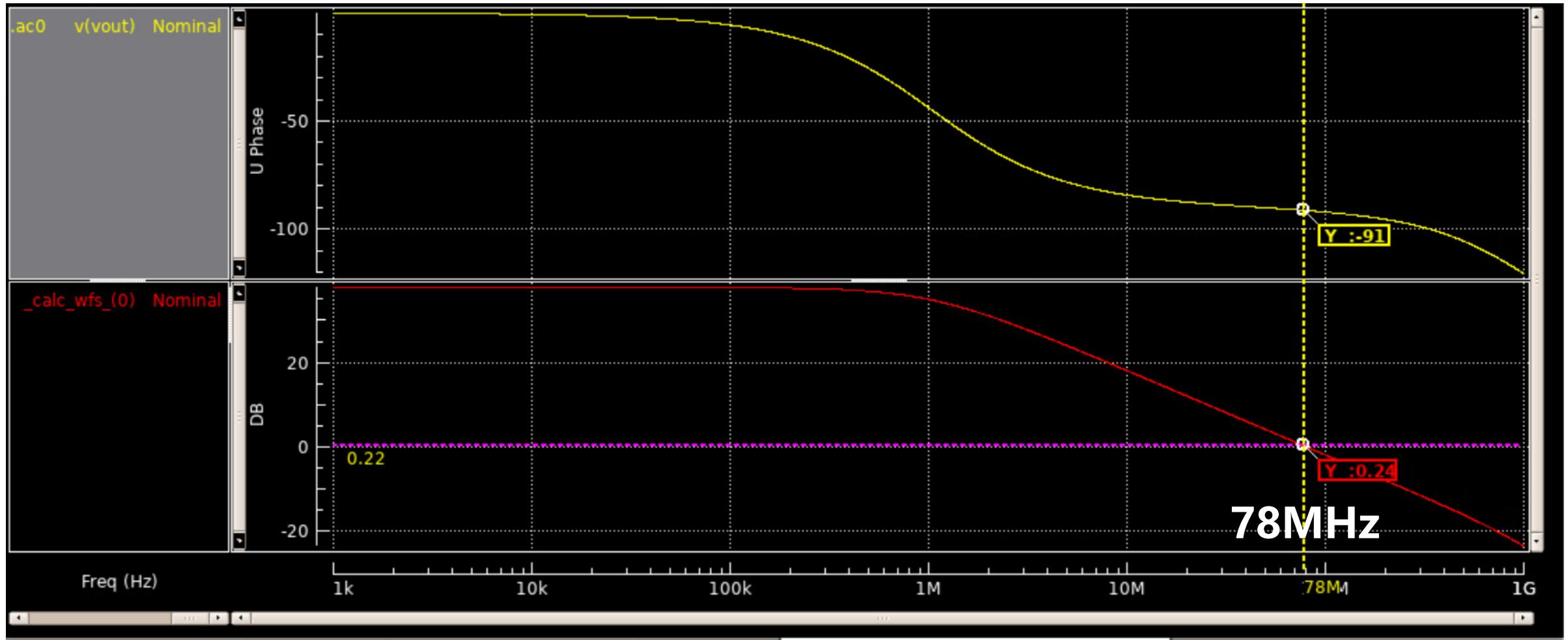
$$I_D = \frac{g_m}{10} = 125.6\mu A/V \quad I_B = 251.2\mu A/V$$

$$\left(\frac{W}{L}\right)_p \approx 80 \quad \left(\frac{W}{L}\right)_n \approx 20$$

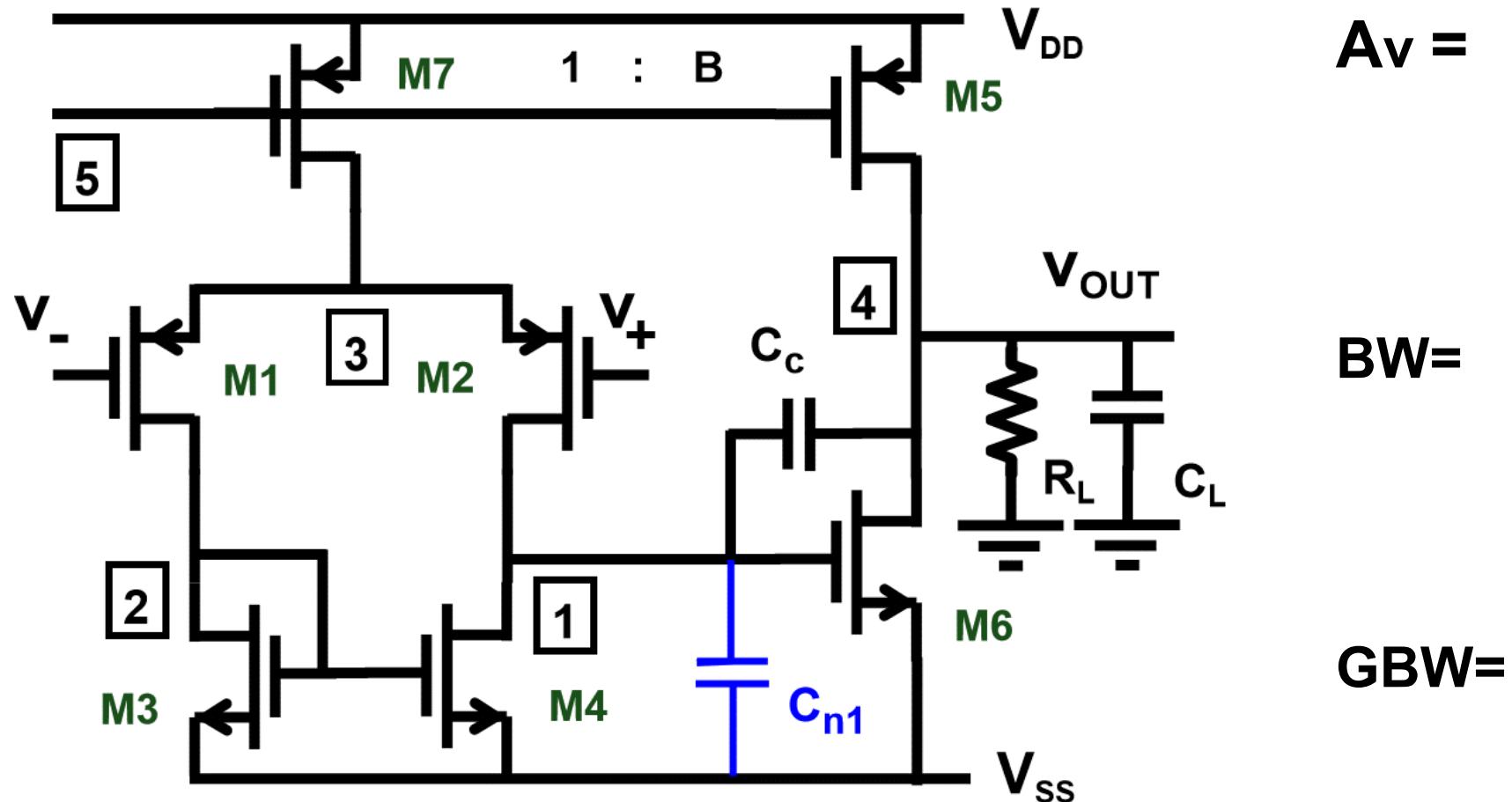
$$\left(\frac{W}{L}\right)_p = \frac{40}{500n} \quad \left(\frac{W}{L}\right)_n = \frac{10}{500n}$$

» 一级OTA的设计

□ 仿真结果

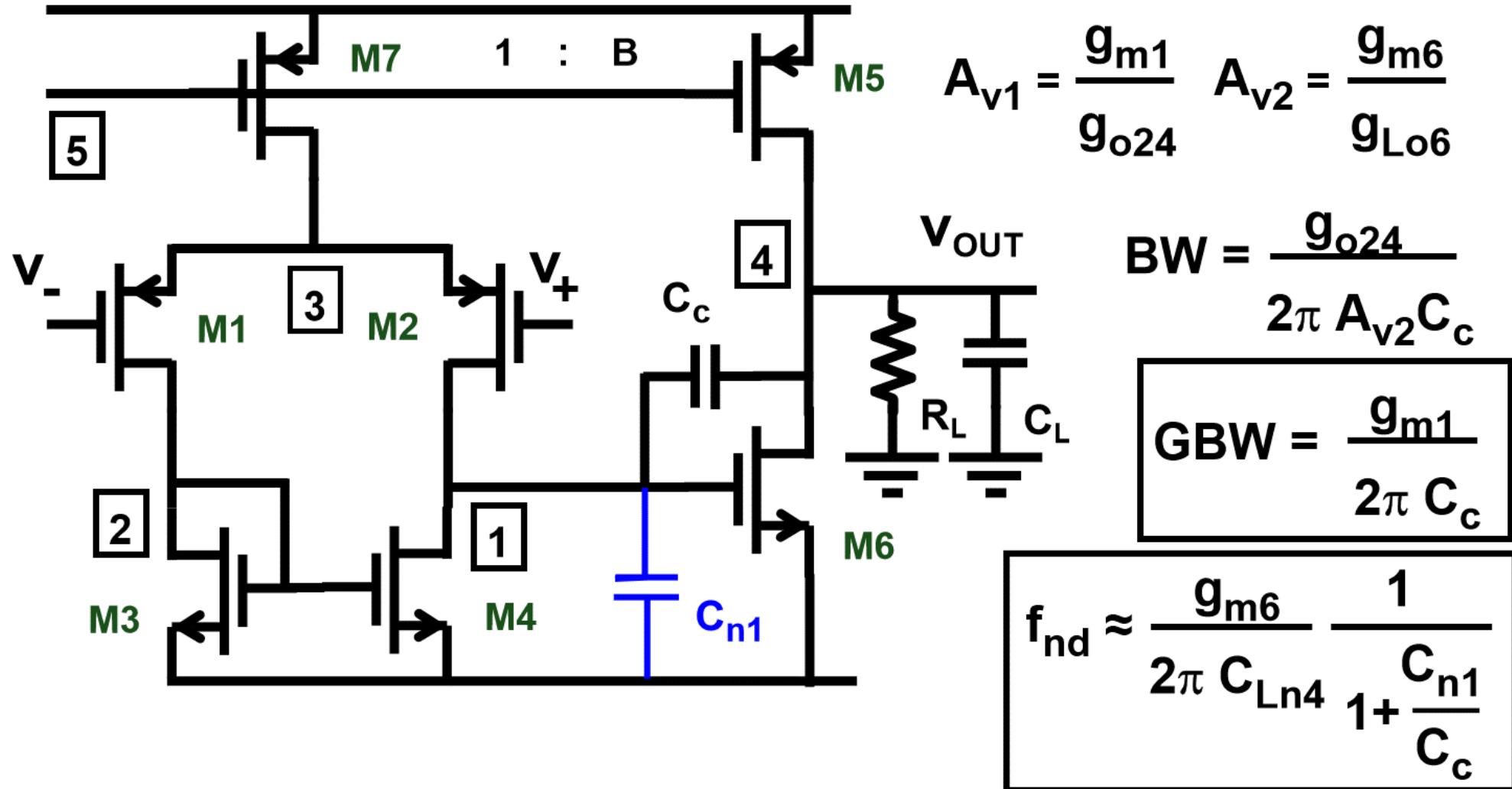


» 二级OTA的设计



□ 二阶体现在哪两个点上?

» 二级OTA的设计





如何设计优化GBW和PM

- 如何在一定的功耗下，获得最优的GBW？
- 已有两个公式，分别定义GBW和PM：

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$$

- 已有三个设计变量：

$$g_{m1}, \quad g_{m6}, \quad C_c$$

如何找到最优的解？



如何设计优化GBW和PM

$$GBW = \frac{g_{m1}}{2\pi C_C} \quad f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$$

1. 先选择 g_{m1} , 根据公式解出 g_{m6} 和 C_C
2. 先选择 g_{m6} , 根据公式解出 g_{m1} 和 C_C
3. 先选择 C_C , 根据公式解出 g_{m1} 和 g_{m6}

C_C 受一定的选择范围限制:

1. 通常大于 $3 \times C_{n1}$
2. 通常小于 $C_L/2$

通过C_C设计优化GBW和PM

□ 要求GBW=1MHz, C_L=10pF。

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$$

假设C_{n1}恒定

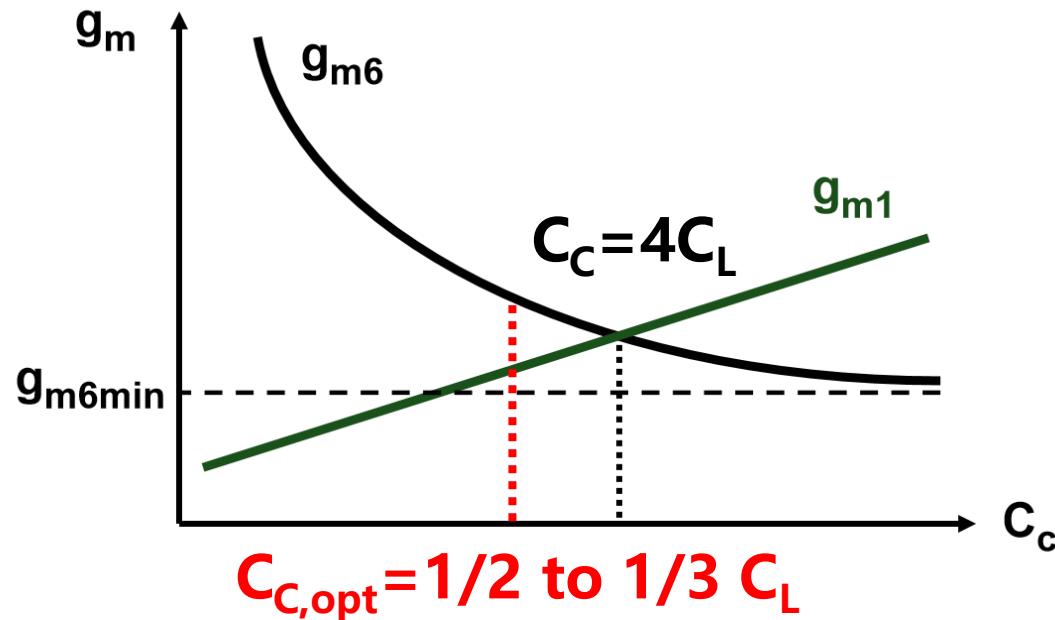


通过 C_C 设计优化GBW和PM

□ 要求 $GBW = 1\text{MHz}$, $C_L = 10\text{pF}$ 。

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$$



寻找 $2*g_{m1} + g_{m6}$ 的最小值

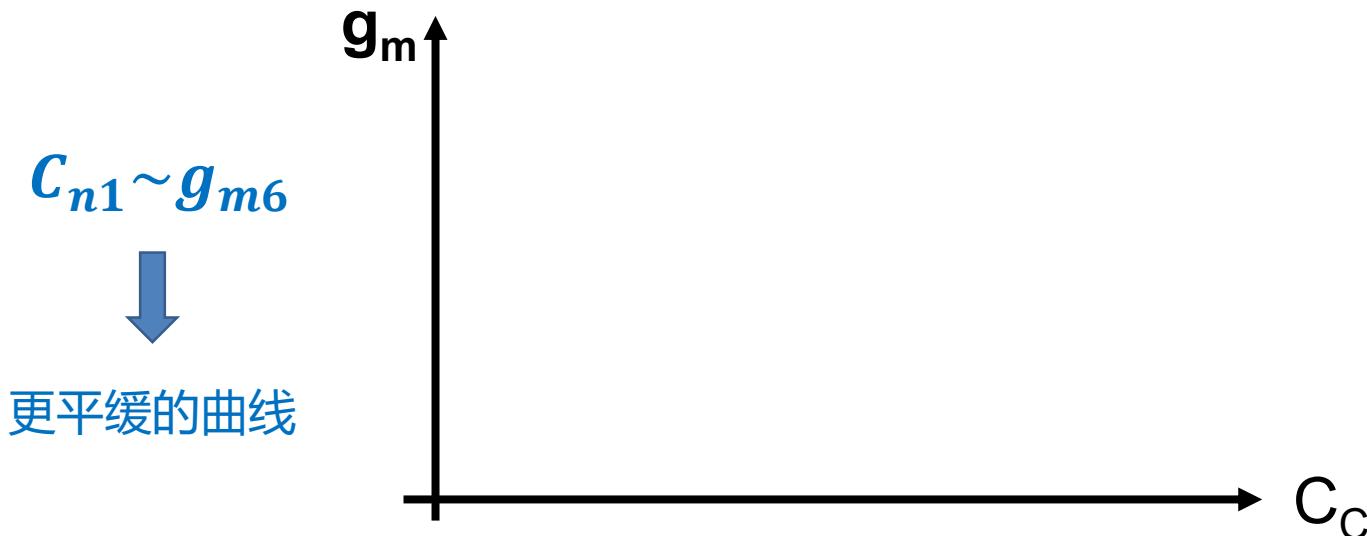
$$C_C = \sqrt{\frac{3}{2} C_{n1} C_L}$$

通过C_C设计优化GBW和PM

□ 要求GBW=1MHz, C_L=10pF。

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}} \text{ 假设C}_{n1}\text{变化}$$

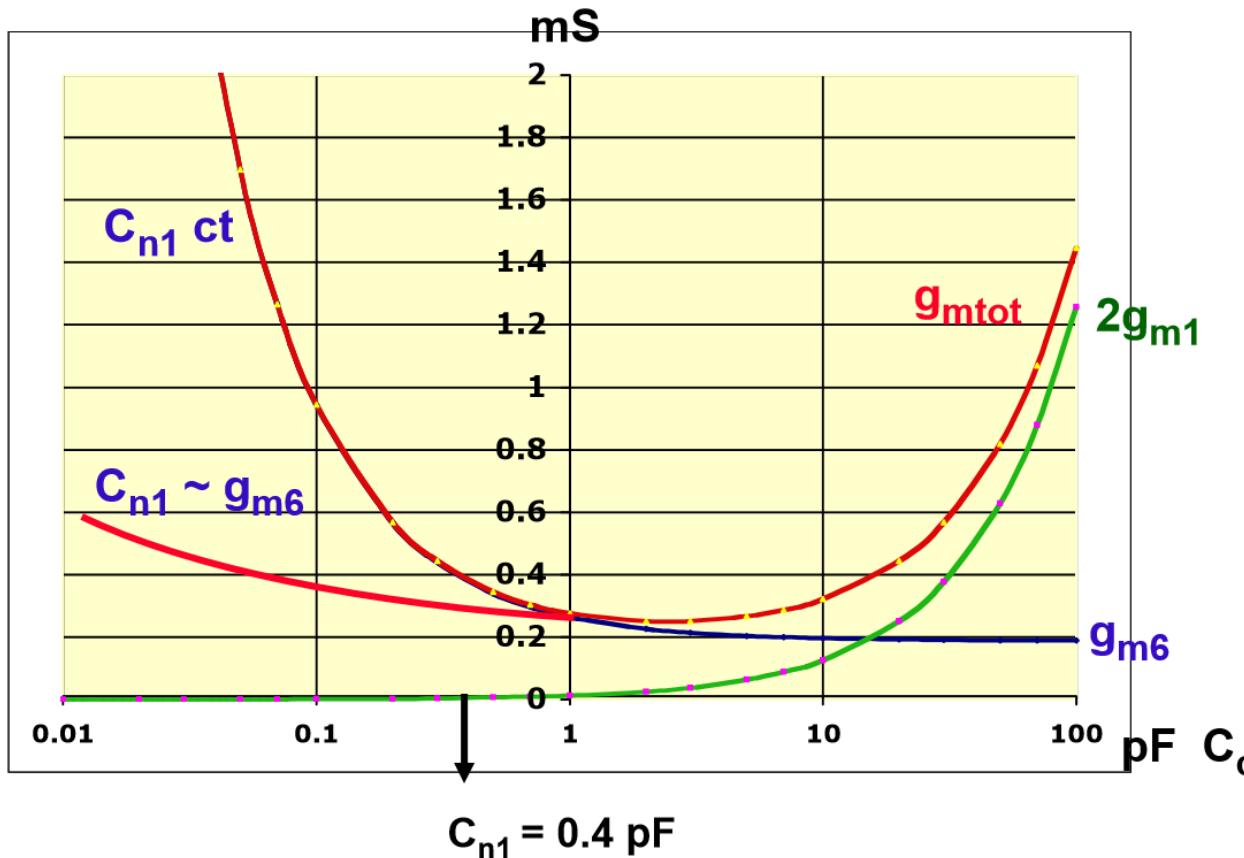


通过 C_C 设计优化GBW和PM

□ 要求 $GBW = 1\text{MHz}$, $C_L = 10\text{pF}$ 。

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_C}}$$





如何设计优化GBW和PM

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$$

1. 先选择 g_{m1} , 根据公式解出 g_{m6} 和 C_C
2. 先选择 g_{m6} , 根据公式解出 g_{m1} 和 C_C
3. 先选择 C_C , 根据公式解出 g_{m1} 和 g_{m6}



通过 g_{m6} 设计优化GBW和PM

□ 要求 $GBW = 1\text{MHz}$, $C_L = 10\text{pF}$ 。

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

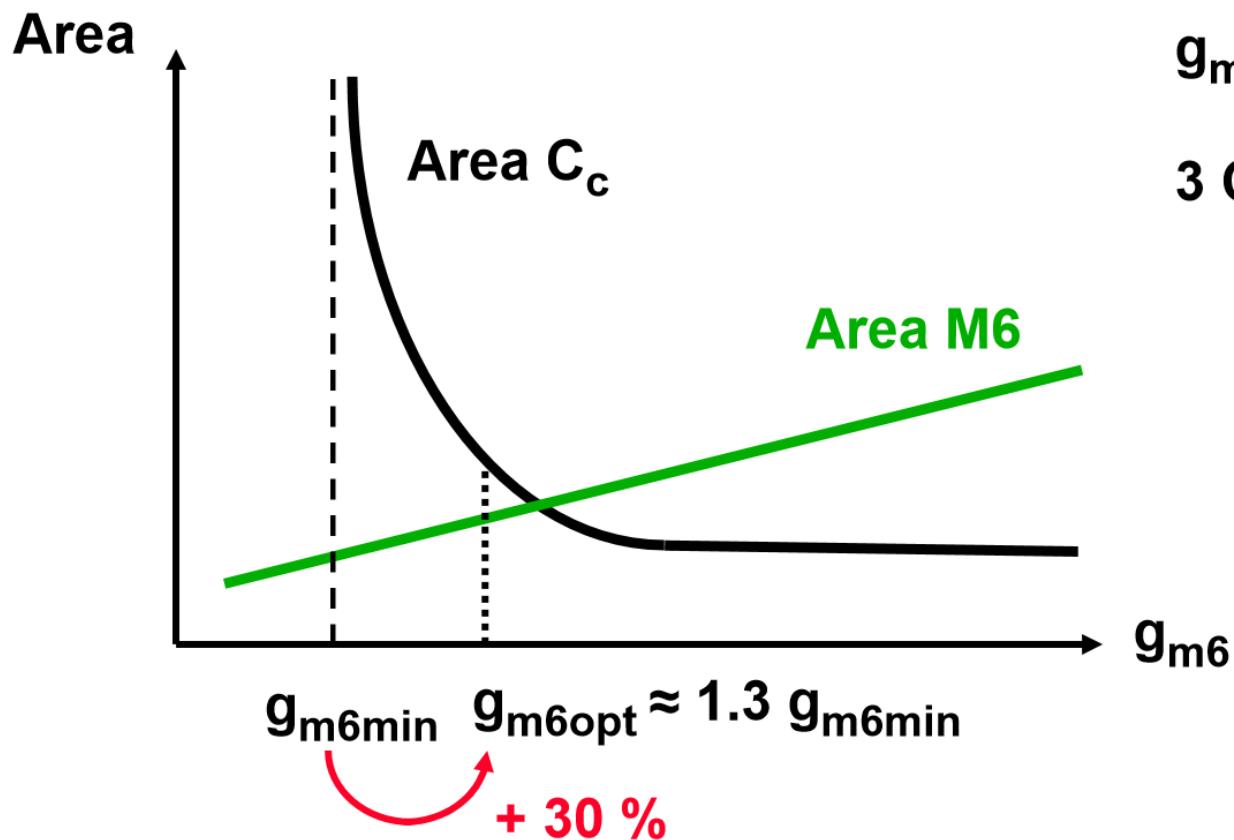
$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}} \quad \text{假设} C_{n1} \text{恒定}$$



通过 g_{m6} 设计优化GBW和PM

□ 要求 $GBW = 1\text{MHz}$, $C_L = 10\text{pF}$ 。

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



$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$$

假设 C_{n1} 恒定
 $g_{m6min} = 3 \text{ GBW } (2\pi C_L)$

» 如何设计优化GBW和PM

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$$

1. 先选择 g_{m1} , 根据公式解出 g_{m6} 和 C_C
2. 先选择 g_{m6} , 根据公式解出 g_{m1} 和 C_C
3. 先选择 C_C , 根据公式解出 g_{m1} 和 g_{m6}

➤对噪声有要求时, 通常先计算 g_{m1}

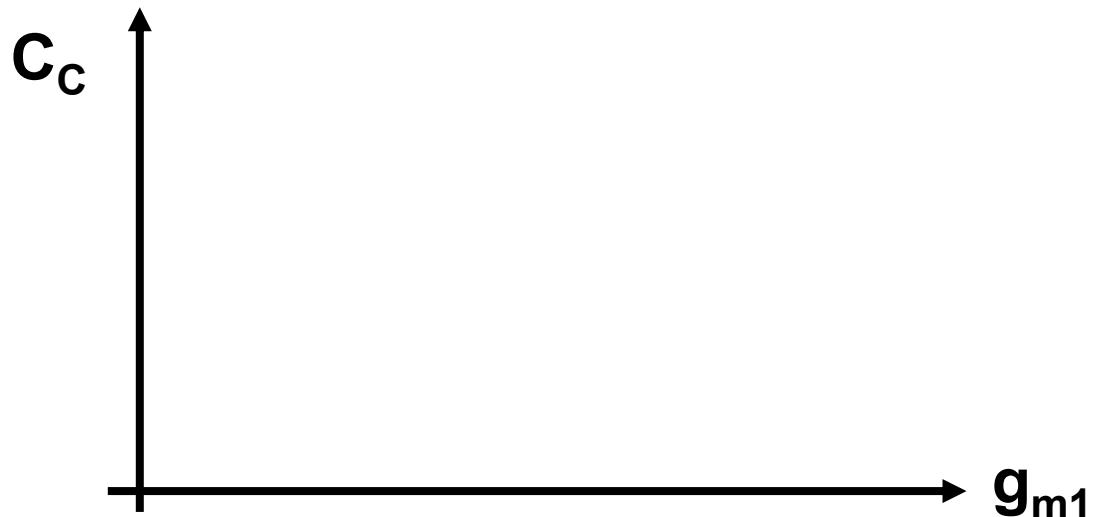
通过 g_{m1} 设计优化GBW和PM

□ 要求 $GBW = 1\text{MHz}$, $C_L = 10\text{pF}$ 。

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}}$$

假设 C_{n1} 恒定

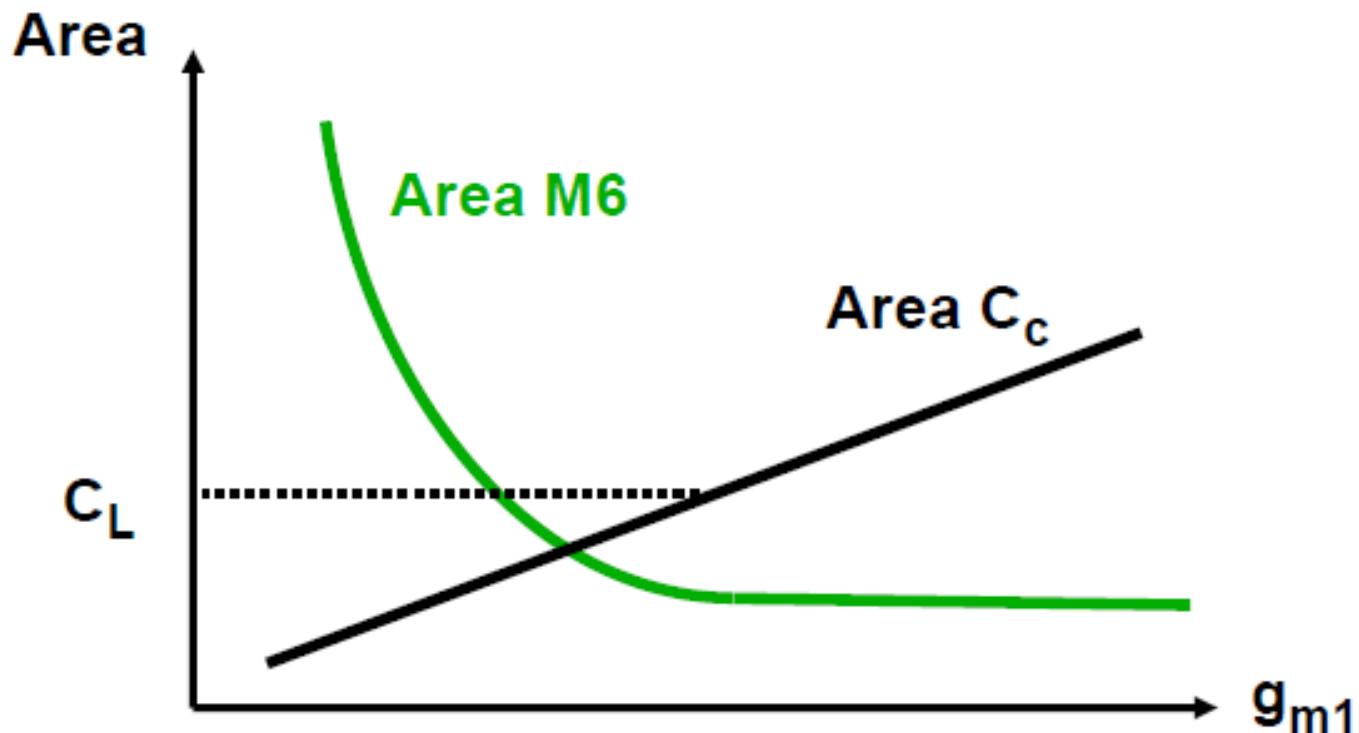


通过 g_{m1} 设计优化GBW和PM

□ 要求 $GBW = 1\text{MHz}$, $C_L = 10\text{pF}$ 。

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + \frac{C_{n1}}{C_c}} \quad \text{假设} C_{n1} \text{恒定}$$



» 高速米勒OTA设计

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + C_{n1}/C_c}$$

$$\text{GBW} = \frac{f_{T6}}{\alpha \beta \gamma (1 + 1/\beta)}$$

$$C_L = \alpha C_c$$

$$C_c = \beta C_{n1} = \beta C_{GS6}$$

$$f_{nd} = \gamma \text{GBW}$$

首先判断某个工艺是否满足指标要求 → 最小长度下的带宽

- GBW不取决于 C_L , 而是取决于输出级晶体管的特征频率

» 高速米勒OTA设计

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

$$f_{nd} = \frac{g_{m6}}{2\pi C_L} \frac{1}{1 + C_{n1}/C_c}$$

$$C_L = \alpha C_c \quad \alpha \approx 2$$

$$C_c = \beta C_{n1} = \beta C_{GS6} \quad \beta \approx 3$$

$$f_{nd} = \gamma GBW \quad \gamma \approx 2$$

$$C_{GS} = kW \quad k = 2fF/\mu m, \text{ for minL}$$

$$GBW = \frac{f_{nd}}{\gamma} = \frac{g_{m6}}{2\pi C_L} \frac{1}{\gamma (1 + 1/\beta)}$$

g_{m6}的表达式?

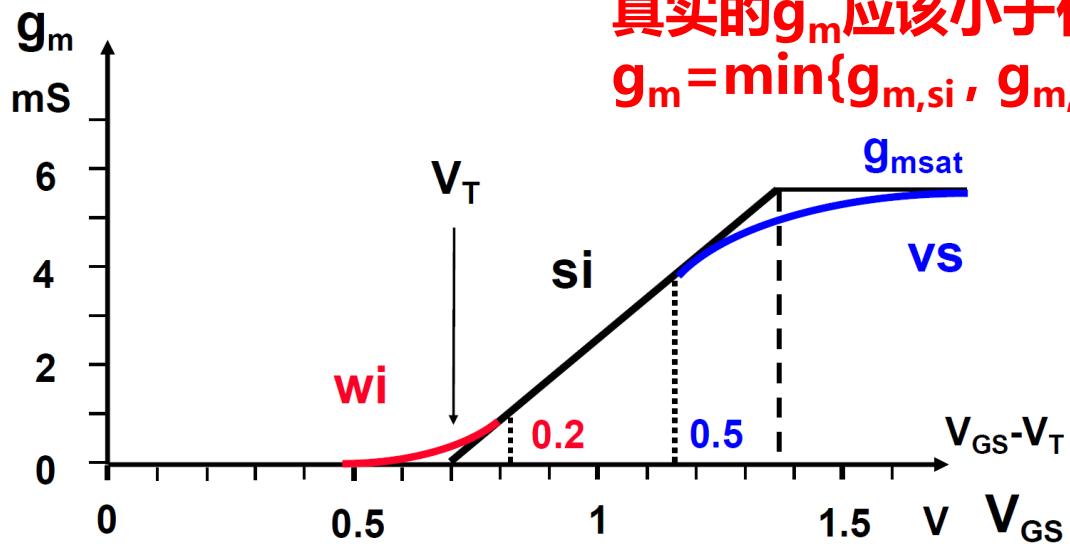
$$C_L = \alpha C_c = \alpha \beta C_{n1} = \alpha \beta C_{GS6} = \alpha \beta kW_6$$

$W_6 \uparrow$ if $C_L \uparrow$

» 高速米勒OTA设计

强反型区(Strong Inversion)

$$g_{m,si} \approx \mu C_{ox} \frac{W}{L} (V_{GS} - V_{TH})$$



速度饱和区(Velocity Saturation)

$$g_{m,sat} = W C_{OX} v_{sat}$$

真实的 g_m 应该小于任意一个表达式
 $g_m = \min\{g_{m,si}, g_{m,sat}\}$

$$\frac{1}{g_m} = \frac{1}{g_{m,si}} + \frac{1}{g_{m,sat}}$$

当取最小长度时

$$g_m \approx \frac{W}{L} \frac{17 \cdot 10^{-5}}{1 + 2.8 \cdot 10^4 L / V_{GST}}$$

L
in cm



高速米勒OTA设计

消除 C_L :

$$GBW = \frac{g_{m6}}{\underbrace{2\pi kW_6}_{f_{T6}}} \frac{1}{\alpha \beta \gamma (1 + 1/\beta)}$$

$$g_m = \frac{W}{L} \frac{17 \cdot 10^{-5}}{1 + 2.8 \cdot 10^4 L / V_{GST}}$$

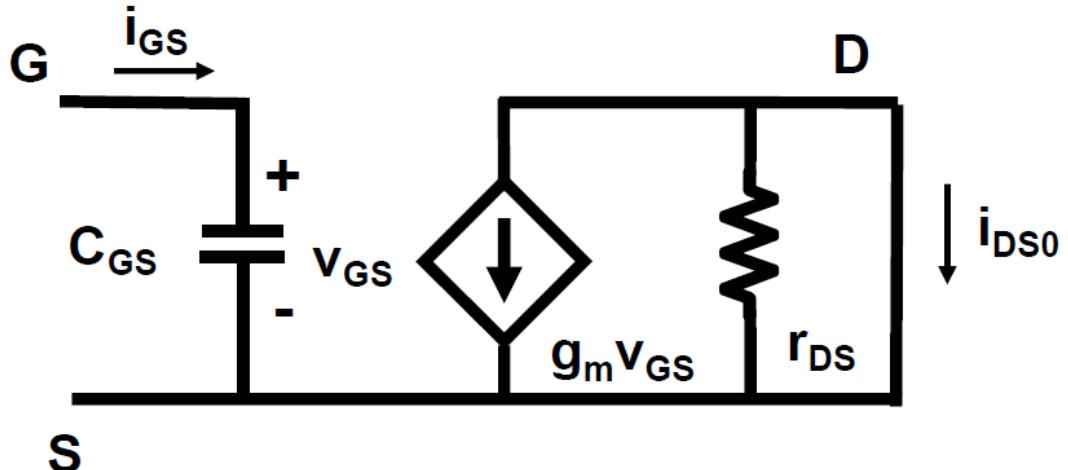
W, L in cm

$$GBW = \frac{1}{2\pi L_6} \frac{1}{\alpha \beta \gamma (1 + 1/\beta)} \frac{8.5 \cdot 10^6}{1 + 2.8 \cdot 10^4 L_6 / V_{GST6}}$$

L in cm

- GBW不取决于 C_L , 而是取决于输出级晶体管的特征尺寸和偏置

» 特征频率 f_T , $i_{DS} = i_{GS}$



$$i_{GS} = v_{GS} C_{GS} s$$

$$i_{DS} = g_m v_{GS}$$

$$C_{GS} = \frac{2}{3} WLC_{ox} \quad g_m = 2K' \frac{W}{L} (V_{GS} - V_T)$$

$$K' = \frac{\mu C_{ox}}{2n}$$

$$f_T = \frac{g_m}{2\pi C_{GS}} = \frac{1}{2\pi} \frac{3}{2n} \frac{\mu}{L^2} (V_{GS} - V_T)$$

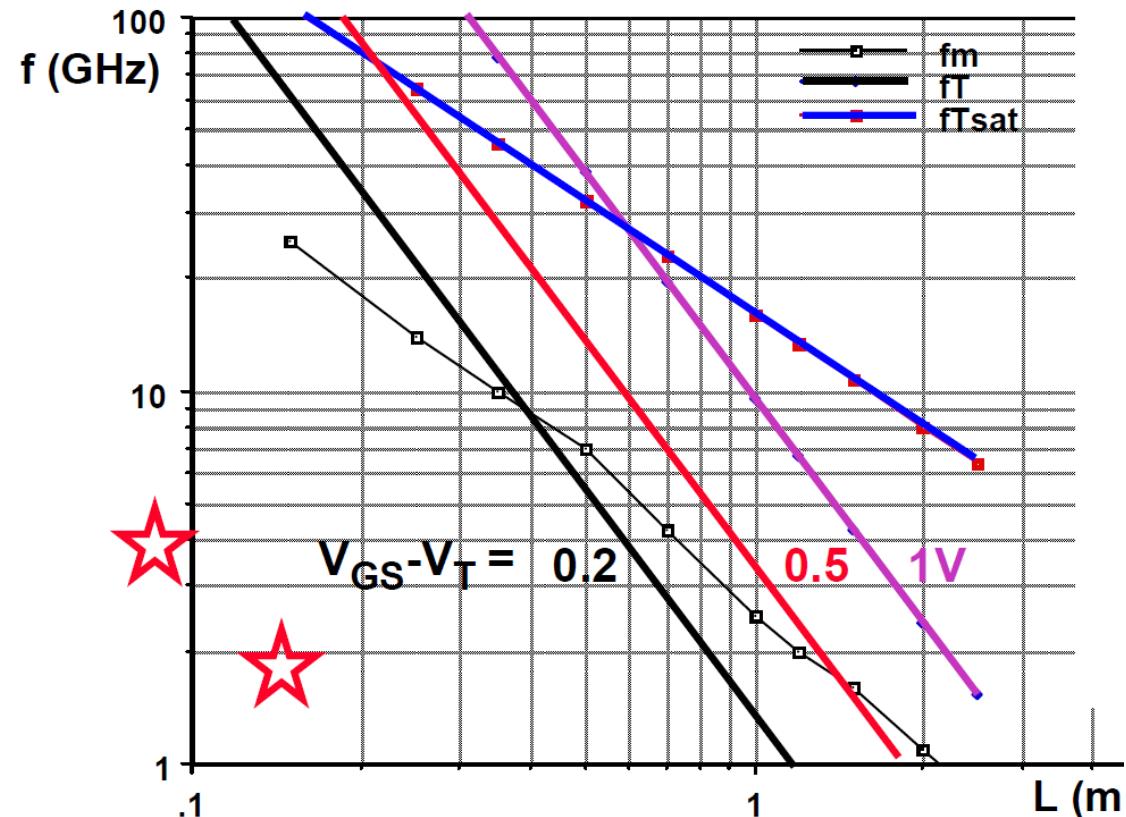
↑
反型区

or

$$\approx \frac{V_{sat}}{2\pi L}$$

↑
速度饱和区

» 高速米勒OTA设计



$$V_{GS} - V_T \approx 0.2 \text{ V}$$

$$\alpha \approx 2$$

$$\beta \approx 3$$

$$\gamma \approx 2$$

or 16 x

$$GBW \approx \frac{f_{T6}}{16}$$

- GBW通常只有 f_T 的1/16
- 如果我们需要5G的GBW，那么需要80G的 f_T ，该指标在0.2V的 V_{GST} 时需要0.1m工艺，而在0.5V的 V_{GST} 时只需要0.2um工艺



高速米勒OTA设计

1. 选择 $\alpha \beta \gamma$
2. 找到满足GBW最小的 f_T
3. 选择一定 $V_{GS6} - V_T$ 下最大的 L_6
4. 根据 C_L 计算 W_6 和偏置电流 I_{DS6}
5. 通过选择的 α 和 C_L 计算 C_C
6. 通过 C_C 计算 g_{m1} 和 I_{DS1}
7. 噪声表现由 g_{m1} 和 C_C 决定

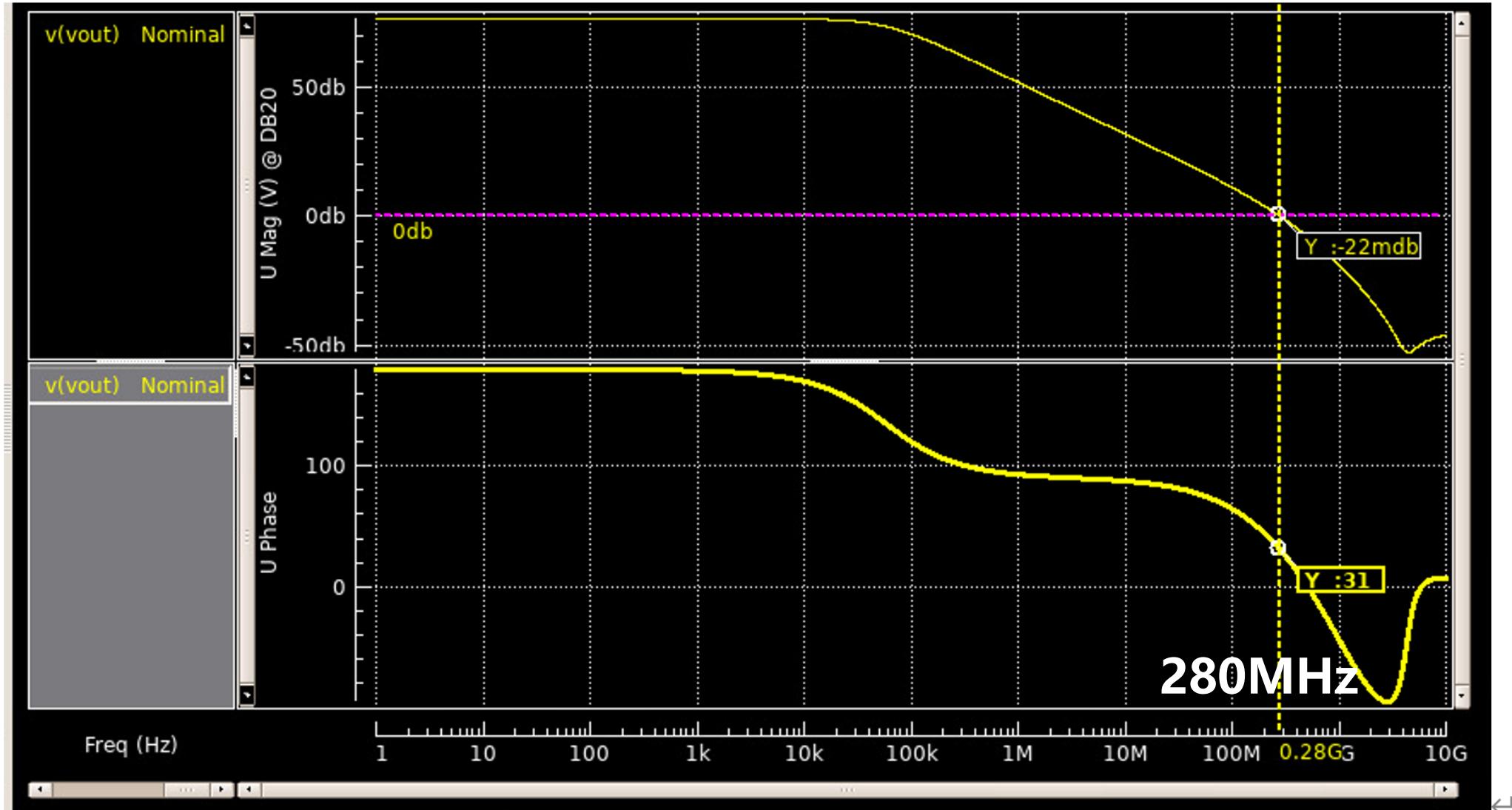


高速米勒OTA设计

□ 要求GBW=400MHz, $C_L=5\text{pF}$ 。

1. 选择 $\alpha \beta \gamma$ • 2 3 2
2. 找到满足GBW最小的 f_T • $f_T=6.4\text{GHz}$
3. 选择一定 $V_{GS6}-V_T$ 下最大的 L_6 • $L_6=0.5\mu\text{m}$
4. 根据 C_L 计算 W_6 和偏置电流 I_{DS6} • $W_6=220\mu\text{m}, I_{DS6}=2.5\text{mA}$
 - $K_n' = 280\mu\text{A}/\text{V}^2$
5. 通过选择的 α 和 C_L 计算 C_C • $C_C=2.5\text{pF}$
6. 通过 C_C 计算 g_{m1} 和 I_{DS1} • $g_{m1}=6.28\text{mS}, I_{DS1}=0.63\text{mA}$
7. 噪声表现由 g_{m1} 和 C_C 决定

》》 高速米勒OTA设计





低功耗米勒OTA设计

高速设计步骤：

1. 选择 $\alpha \beta \gamma$
2. 找到满足GBW最小的 f_T
3. 选择一定 $V_{GS6} - V_T$ 下最大的 L_6
4. 根据 C_L 计算 W_6 和偏置电流 I_{DS6}
5. 通过选择的 α 和 C_L 计算 C_C
6. 通过 C_C 计算 g_{m1} 和 I_{DS1}
7. 噪声表现由 g_{m1} 和 C_C 决定

低功耗设计步骤：

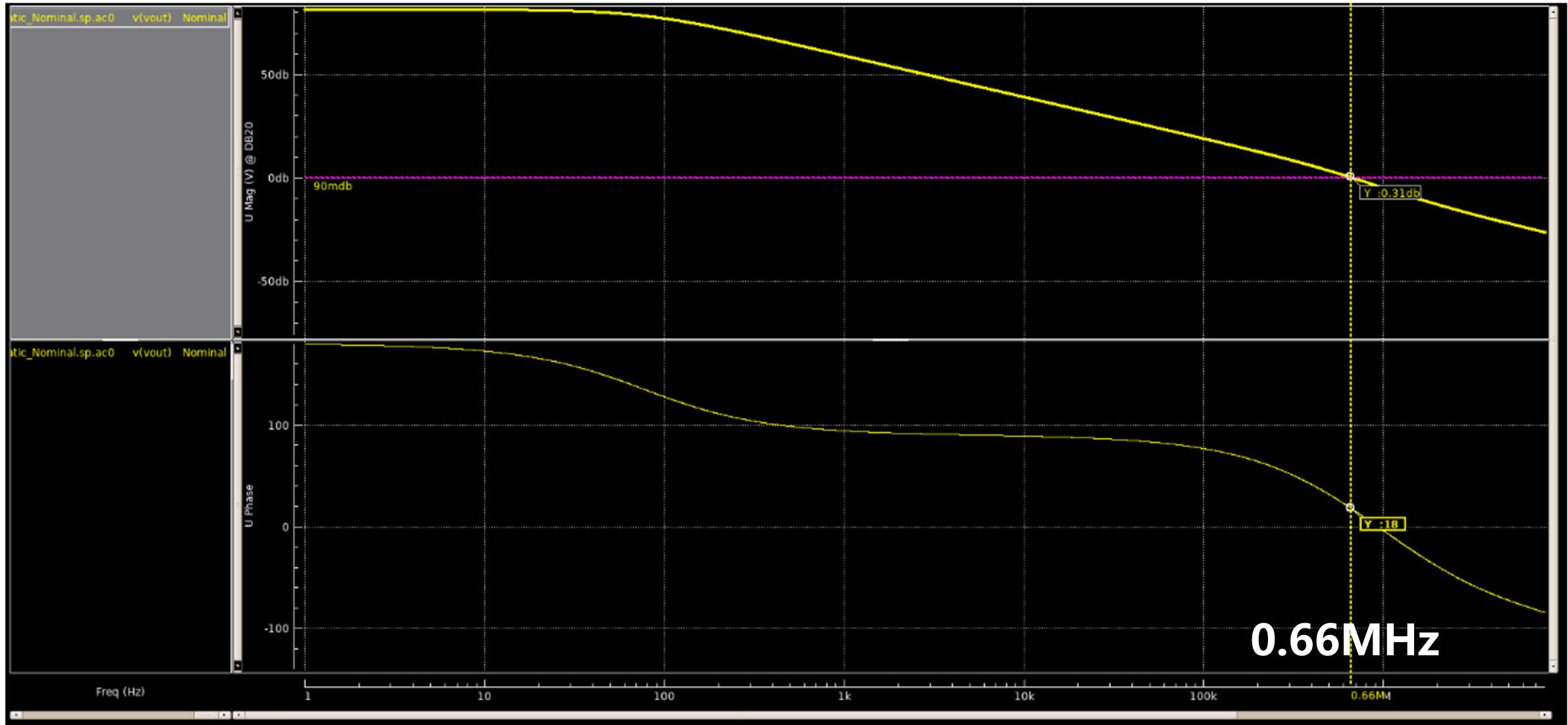
1.
$$f_T = \frac{2\mu kT/q}{2\pi L^2} \cdot \sqrt{i(1 - e^{\sqrt{i}})}$$
2. 尺寸设计 偏置设计
3. 根据情况选择反型系数 i
4. 根据 C_L 和 L_6 计算 W_6
5. 根据 I_{DST6} 和 反型系数 i 计算 I_{DS6}
- 6.
- 7.

» 低功耗米勒OTA设计

□ 要求GBW=1MHz, $C_L=5\text{pF}$ 。

1. 选择 $\alpha \beta \gamma$ • 2 3 2
2. 找到满足GBW最小的 f_T • $f_T=16\text{MHz}$
3. 根据增益要求选择 L_6 • $L_6=0.5\mu\text{m}$
 - 得到 f_{TH6} $f_{TH6}=6.4\text{GHz}, i=2.5\text{m}$
4. 根据 C_L 和 L_6 计算 W_6 • $W_6=220\mu\text{m}$
5. 根据 I_{DST6} 和反型系数*i*计算 I_{DS6} • $I_{DST6}=0.31\text{mA}$
 - $K_n' = 280\mu\text{A}/\text{V}^2$ • $I_{DS6}=0.8\mu\text{A}$
6. 通过选择的 α 和 C_L 计算 C_C • $C_C=2.5\text{pF}$
7. 通过 C_C 计算 g_{m1} 和 I_{DS1} • $I_{DS1}=0.6\mu\text{A}$

》》低功耗米勒OTA设计





运放的稳定性与系统性设计

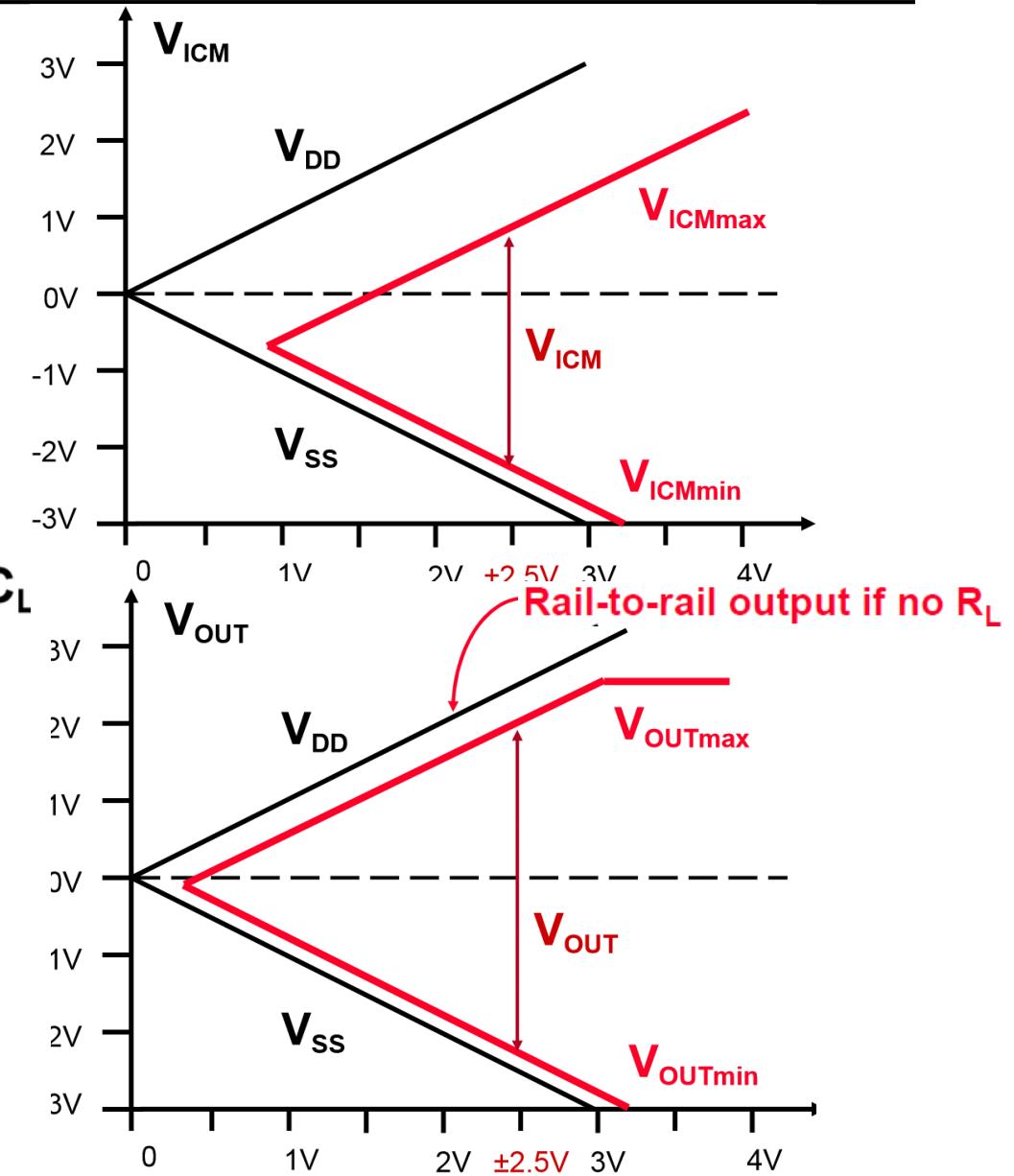
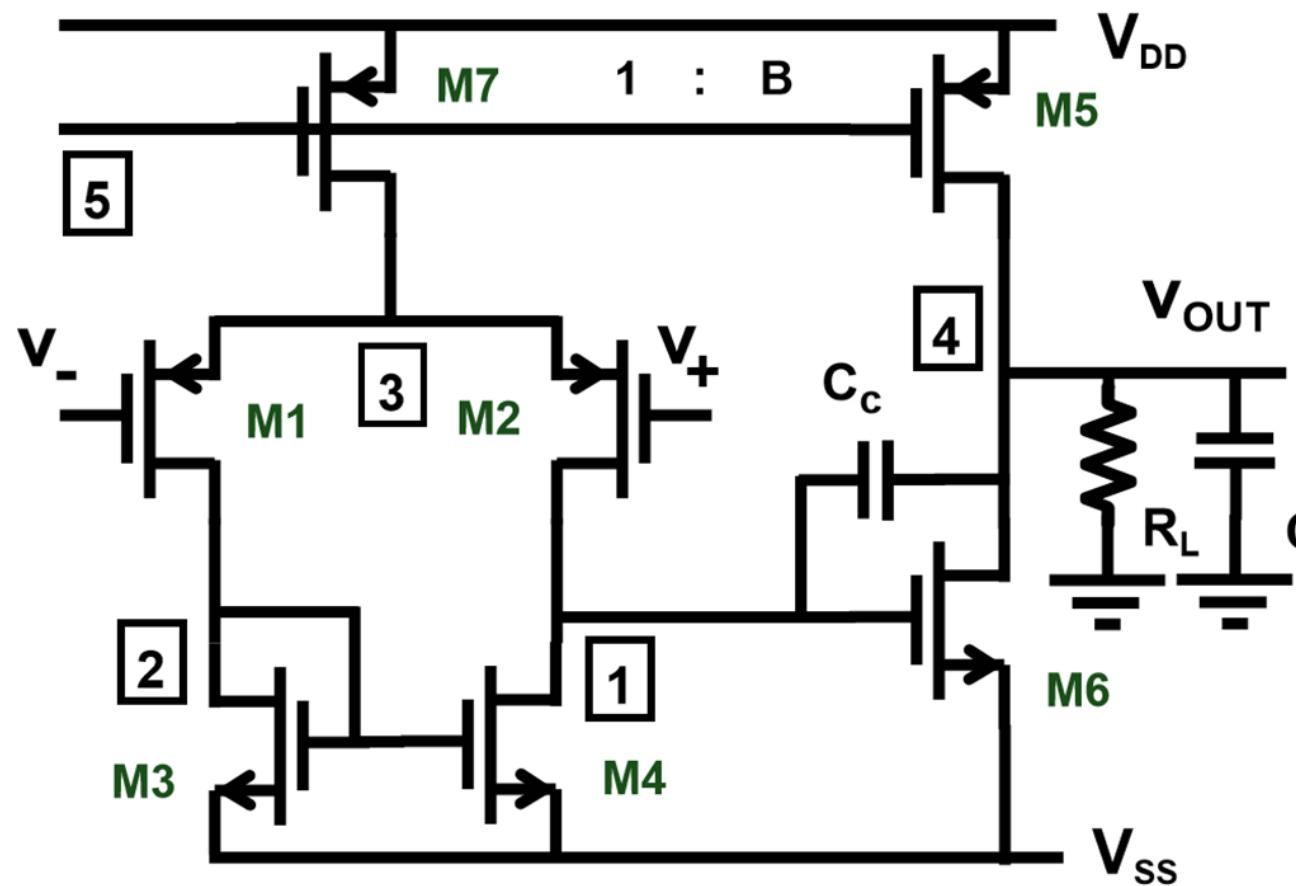
- 运放、反馈与稳定性的基本概念
- 极点分离与零点补偿
- 三级运放稳定性问题简介
- 运放的系统性设计方法
- **运放的其他参数指标**



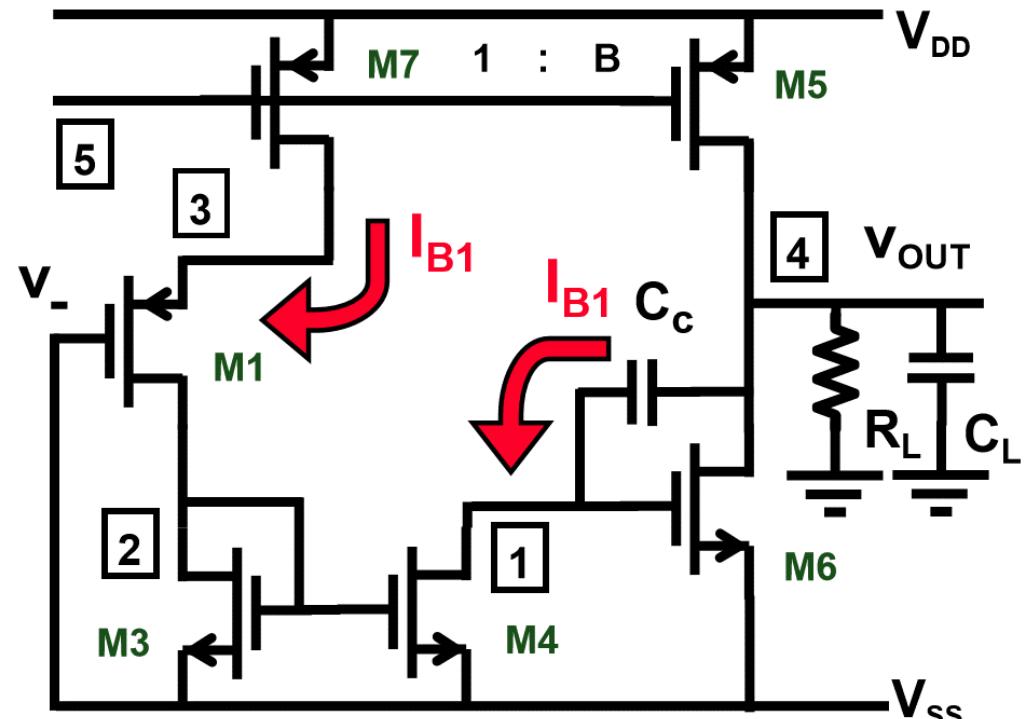
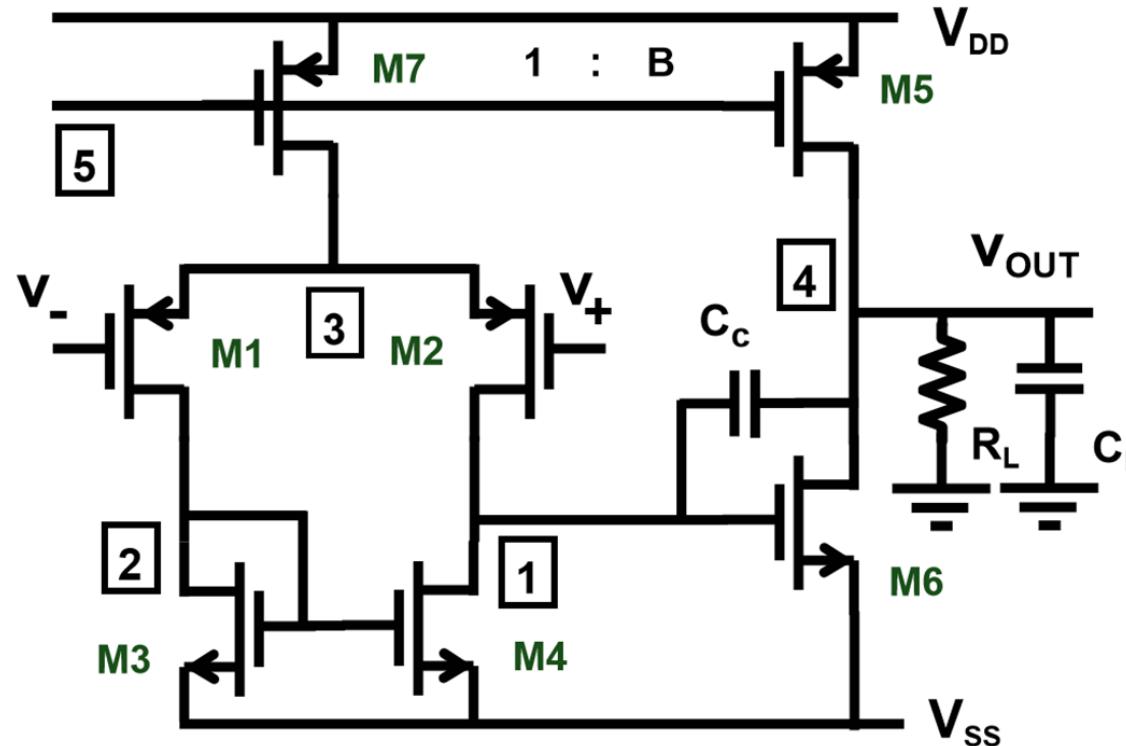
米勒运放的其他指标与分析

- 共模输入电压范围
- 输出电压范围
- 压摆率
- 输出阻抗
- 噪声

米勒运放：共模输入范围/输出范围



》》米勒运放：压摆率

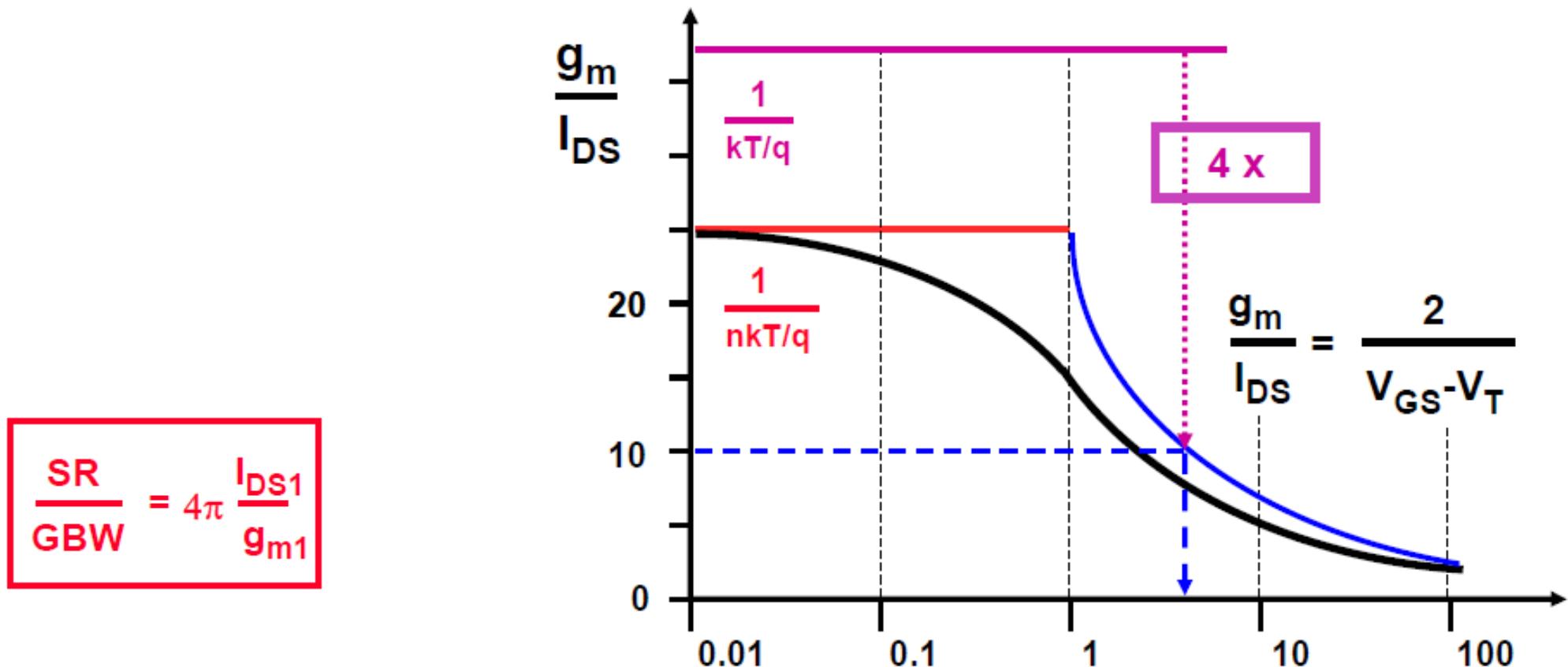


$$SR = \frac{\Delta V_{OUT}}{\Delta t}$$

$$SR = \frac{I_{B1}}{C_c}$$

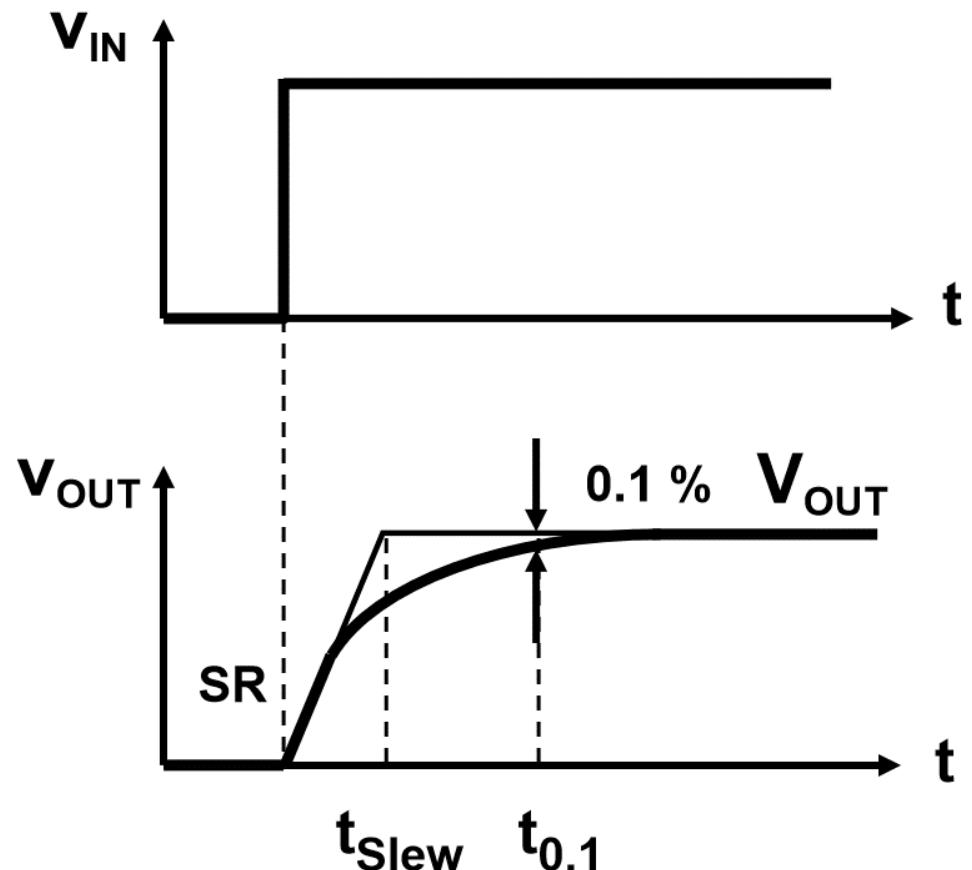
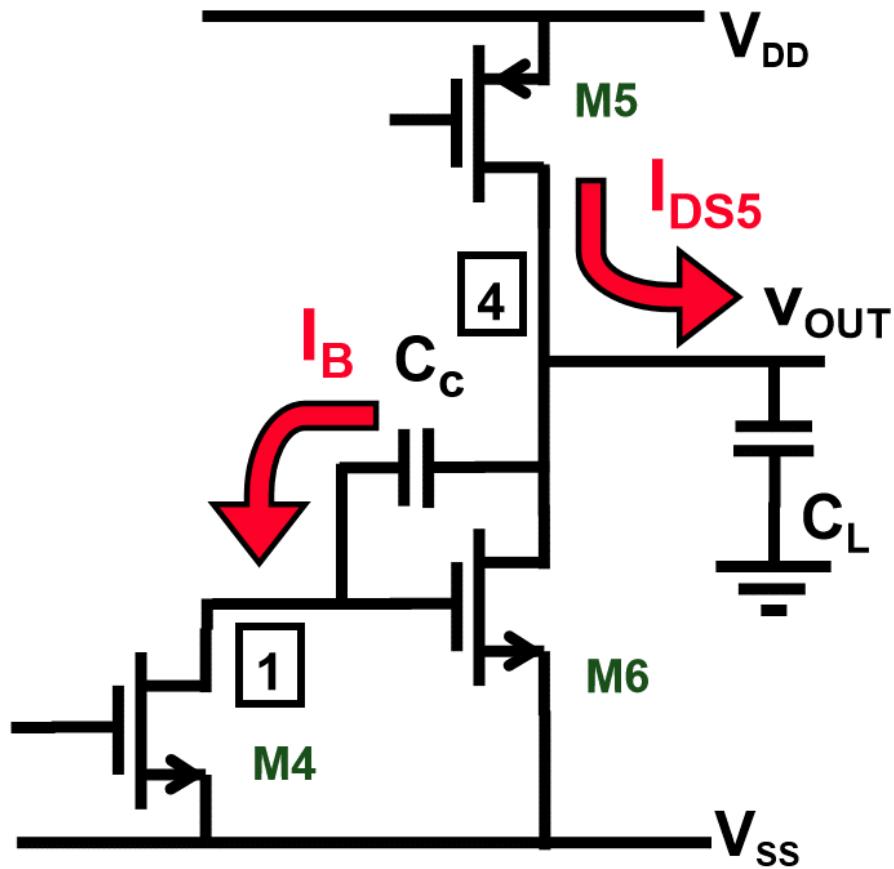
米勒运放：压摆率

□ 如何在GBW不变的情况下提高压摆率？



✓ 从始至终，高速设计始终要求大的 $V_{GS}-V_T$

》》米勒运放：压摆率



- 通常压摆率由补偿电容 C_c 决定
- 但是，外部电容也可以成为压摆率的瓶颈



设计思路总结

1. 初步分析

1. 所有节点上的直流电流和电压
2. 所有晶体管的小信号参数分析

2. 直流分析

1. 共模输入电压范围 vs. 电源电压
2. 输出电压范围 vs. 电源电压
3. 最大输出电流



设计思路总结

3. 交流及瞬态分析

1. 所有节点上的直流电阻和电容
2. 增益的频率响应
3. 增益带宽积 vs 偏置电流
4. 压摆率 vs 负载电阻
5. 输出电压范围 vs 频率
6. 建立时间
7. 输入阻抗 vs 频率
8. 输出阻抗 vs 频率

4. 噪声和失调分析

1. 失调电压 vs 共模输入电压
2. CMRR vs 频率
3. 输入偏置电流
4. 等效输入电压噪声 vs 频率
5. 等效输入电流噪声 vs 频率
6. 容性/感性信号源的噪声优化
7. PSRR vs 频率
8. 失真



设计思路总结

5. 其他效应

1. 电感负载下的稳定性
2. 切换偏置晶体管 (biasing transistors)
3. 切换或扫描电源
4. 不同的电源、温度、工艺等

 课后习题

□已知要求 $GBW=50MHz$, $C_L=5pF$ 。设计一相位裕度大于 70° 的米勒运放。通过仿真结果，给出该设计运放的：

1. FOM
2. 相位裕度
3. 输入等效总噪声