5) 集成运放分类.

按集成度：单运放. 双运放. 四运放

工艺：双极型，单极型. 混合

可控性：{ 可变增益运放. 选通控制运放.

按性能：高阻型. 高速型 高精度. 低功耗型(航天. 航空)，高压型. 大功率

6) 保护电路，低频等效电路.

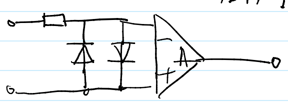
① 防止输入信号过大，击穿PN结.

② 电源接反.

③ 输出端接地或电源. 损坏

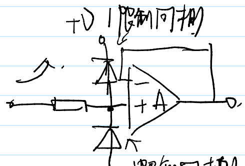
1) 输入

(差模)



D_1 D_2

$D_1.D_2$ 限制差模幅值，R保护二极管.



+V (限制同相)

−V (限制同相)

(共模)

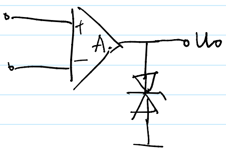
限制同相输入电压.

引入负反馈. 仅同相，反相无限接近.

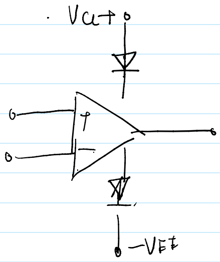
$U_P = U_N$?

因为A大，所以 $U_I \to 1mV$. 十分深度负反馈 $A = \frac{1}{F}$

2) 输出.



控制输出电压.

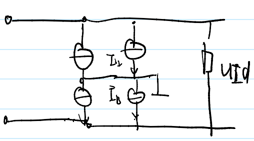


$V_{cc}+$

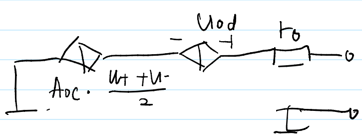
$-V_{EE}$

保护电源

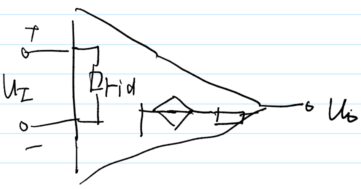
3) 低频等效电路



IN



OUT



理想化

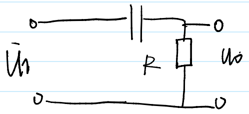
8. 频率响应.

信号频率对放大倍数的影响.

原因：耦合电容，旁路电容. 极间电容

• 基础回顾：

高通电路：$f\uparrow$ $V \to V_{input}$.



$u_i = U_C + i \cdot R$,

$= U_C + \frac{dU_C}{dt} \cdot C \cdot R$

$\rightarrow \frac{dU_C}{dt} + \frac{1}{RC}U_C = \frac{1}{RC}U_i$

设 $U = A\cos wt$

常数变异法：可以参考高数书或微分手稿：

[笔记_常微分方程]

$q(t) = CU(t)$

$\therefore i = \frac{dq}{dt} = C\frac{dU(t)}{dt}$

若 $U = A\sin(wt+\phi)$

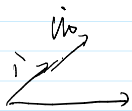
则 $i = jwC \cdot A(\cos wt + \phi)$

电流领先电压 $\frac{\pi}{2}$ 个相位.

且容抗为 $\frac{1}{jwC}$

$\therefore U_o = \frac{R}{\frac{1}{jwC}+R} U_i$

$w\uparrow \to \frac{1}{jwC}+R \approx R$ $\therefore$ 为高通电路.



U_o

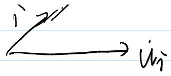
i

U_i

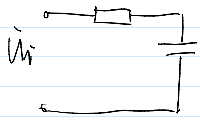
因流领先电压 $\frac{\pi}{2}$ 个相位.
且容抗为 $\frac{1}{j\omega C}$

$\omega\uparrow \to \frac{1}{\frac{1}{j\omega C}+R} \approx R$

$\omega\downarrow \to \frac{R}{\frac{1}{j\omega C}+R} \approx 0$. ∴为高通电路.



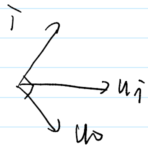
低通电路:



$\dot{U}_o = \frac{1}{1+j\omega CR}\dot{U}_i$

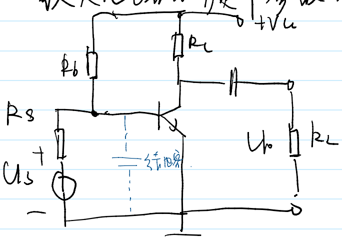
$\omega\uparrow$ $\dot{U}_o \approx 0$

$\omega\downarrow$ $\dot{U}_o \approx \dot{U}_i$



当输出电压下降为 $\frac{1}{\sqrt{2}}\dot{U}_i$.

- 放大电路的频率参数.

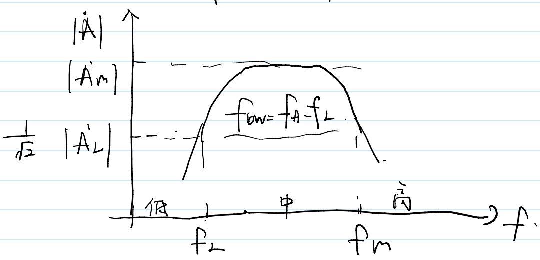


这是一个高通电路.

在低频段, 耦合电容和旁路电容等容抗较大, 使动态信号损失, 放大能力下降. 超前相角

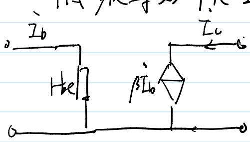
中输入端的结电容相当于低通电路. 使放大倍数下降. 滞后相角.

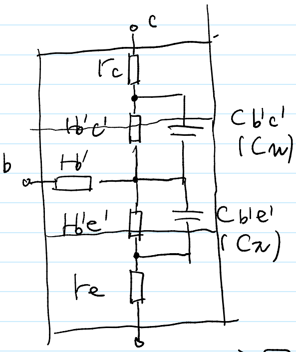
分布电容, 寄生电容 | 集成运放中电路设计.



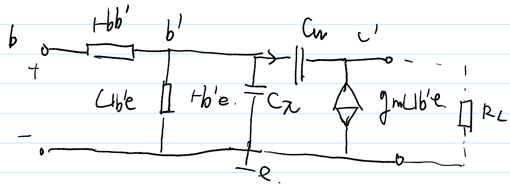
- 晶体管高频等效电路.

低频等效模型





晶体管结构示意图



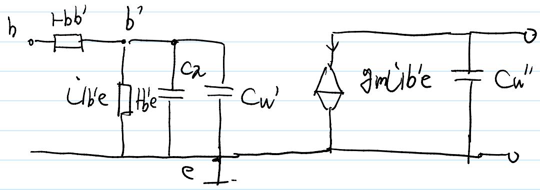
C_π. 发射结电容

C_μ, 集电结上电容.

$r_{b'c'}$ 很大可忽略.

C_μ 即影响输入回路, 还影响输出回路.

可以将 C_μ 等效到两个回路上.



等效的思路

不能改变电流的大小

(将 C_μ 拆到两个回路上)

$I_{C\mu}' = \frac{U_{b'e} - U_{c'e}}{X_{C\mu}} = (1-k)\frac{U_{b'e}}{X_{C\mu}}$

$X_{C\mu}$: C_μ 的电抗

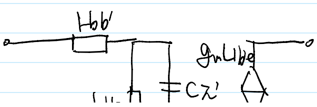
$U_{c'e} = kU_{b'e}$, $k \approx -g_m R_L'$

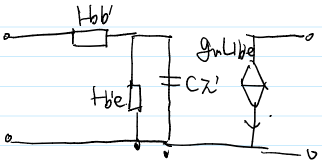
$X_{C\mu}' = \frac{U_{b'e}}{I_{C\mu}'} = \frac{U_{b'e}}{(1-k)\frac{U_{b'e}}{X_{C\mu}}} = \frac{X_{C\mu}}{1-k} = \frac{X_{C\mu}}{1+g_m R_L'}$

$\boxed{C_\mu' \approx (1+g_m R_L')C_\mu}$

$X_{C\mu}'' = \frac{U_{c'e}}{I_{C\mu}'} = \frac{-kU_{b'e}}{(1-k)\frac{U_{b'e}}{X_{C\mu}}} = \frac{k}{1-k}X_{C\mu} = \frac{-g_m R_L'}{1+g_m R_L'}X_{C\mu}$.

$C_\mu'' = \frac{1-k}{...}$





简化后无 C_μ'' 的等效电路。

$$X_{C\mu}'' = \frac{\dot U_{c'e}}{\dot I'_{C\mu}} = \frac{-k\dot U_{b'e}}{(1-k)\frac{\dot U_{b'e}}{X_{C\mu}}} = \frac{k}{1-k}X_{C\mu} = \frac{-g_m R_L'}{1+g_m R_L'}X_{C\mu}$$

$$\boxed{C_\mu'' = \frac{1-k}{k}X_{C\mu}} \approx C_\mu$$

简化：不考虑 C_μ''，$C_\pi' = C_\pi + C_\mu' = C_\pi + (1+|k|)C_\mu$

C_μ'' 的容抗较大，可以开路。

主要参数 $r_{b'e} = (1+\beta_0)\frac{U_T}{I_{EQ}}$，$\beta_0$ 为低频段放大

$$\dot I_c = g_m \dot U_{b'e} \approx \beta_0 \dot I_b$$

$$\because g_m \dot I_b \cdot r_{b'e} = \beta \dot I_b$$

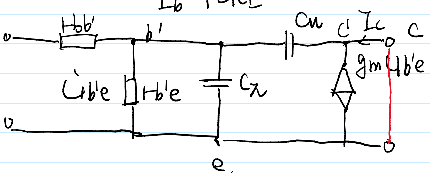
$$\therefore g_m = \frac{\beta_0}{r_{b'e}} \approx \frac{I_{EQ}}{U_T}$$

根据半导体物理分析，晶体管的受控电流 $\dot I_c$ 和发射结电压 $\dot U_{b'e}$ 成线性关系，不受频率影响，所以混π模型中都用 g_m

- 晶体管放大电路频率响应。

$$\dot\beta = \frac{\dot I_c}{\dot I_b}\Big|_{U_{CE}}$$

可以短接ce，没有记载输入时 $u_{ce}=0$ 且不变，则可以短接。



$$\dot I_c = g_m \dot U_{b'e} = \beta_0 / r_{b'e} \cdot \dot U_{b'e}$$

$$\dot I_b = \dot U_{b'e}\left(\frac{1}{r_{b'e}} + j\omega C_\pi + j\omega C_\mu\right)$$

$$\therefore \dot\beta = \frac{\frac{\beta_0}{r_{b'e}}\cdot \dot U_{b'e}}{\left[\frac{1}{r_{b'e}} + j\omega(C_\pi + C_\mu)\right]\cdot \dot U_{b'e}} = \frac{\beta_0}{1 + r_{be'}\cdot j\omega(C_\pi + C_\mu)}$$ 与 $\frac{1}{1+j\omega RC}$ 一样。

可以看成低通电路

f_β 为 β 的共射截止频率，$r_{be'}(C_\pi \cdot C_\mu)\omega = 1$ 时，$f_\beta = \frac{1}{2\pi r_{b'e}C_\pi'}$

此时 β 为 $\frac{1}{\sqrt2}\beta_0$，$f_\beta = \frac{1}{2\pi\tau}$

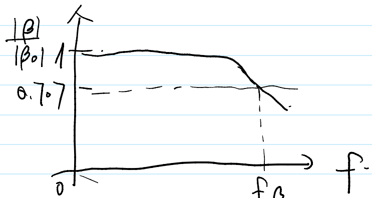
这时 $\dot\beta = \frac{\beta_0}{1+j2\pi f\cdot\tau} = \frac{\beta_0}{1+j\frac{f}{f_\beta}}$

$$\begin{cases} |\dot\beta| = \frac{\beta_0}{\sqrt{1+\left(\frac{f}{f_\beta}\right)^2}} \\ \varphi = -\tan^{-1}\frac{f}{f_\beta} \end{cases}$$

若 $f \ll f_\beta$ 时，$|\dot\beta| \approx \beta_0$

若 $f = f_\beta$ 时 $|\dot\beta| = \frac{\beta_0}{\sqrt2}$，$\varphi = -45°$

若 $f \gg f_\beta$ 时 $f\to\infty$ $|\dot\beta|\to 0$ $\varphi \to -90°$



幅频特性曲线

相频特性曲线

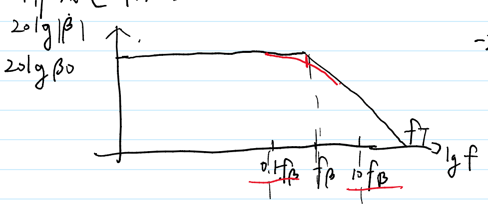
$\sqrt{1+\left(\frac{f}{f_\beta}\right)^2} = \beta_0$ 时，$f = f_T$

$$f_T \approx \beta_0 \cdot f_\beta$$

$$\because \dot\alpha = \frac{\dot\beta}{1+\dot\beta} = \frac{\frac{\beta_0}{1+jf/f_\beta}}{1+\frac{\beta_0}{1+jf/f_\beta}} =$$

$$\therefore \dot\alpha = \frac{\alpha_0}{1+j\frac{f}{f_\alpha}} \rightarrow f_\alpha = (1+\beta_0)f_\beta$$

折线近似。



$-20\,dB/$十倍频

误差：$20\lg\sqrt2 \approx 3dB$

误差：5.71°

如果：

开闭状态，"×"变"+"

☆ f_α 共基截止频率，$\frac{\Delta I_c}{\Delta I_e} = \frac{\beta}{1+\beta}$

☆ f_T β 下降为1的频率

$f_T \approx f_\alpha \approx f_\beta \cdot \beta$

共基时的带宽比共射大 β 倍

☆ $C_{ob}(C_\mu)$ 集电结电容

☆ $C_\pi' = C_\pi + C_\mu$ 代换

$0.1f_\beta$，$10f_\beta$ 对称翻转用

设出结论

1) 高频段放大倍数的表达式

2) 截止频率与时间常数的关系，$f_\beta = \frac{1}{2\pi\tau} = \frac{1}{2\pi r_{b'e}\cdot(C_\pi + C_\mu)}$

3) 渐近线画法，误差

2) 截止频率与时间常数的关系。 $f_\beta = \frac{1}{2\pi\tau} = \frac{1}{2\pi r_{b'e}\cdot(C_\pi + C_\mu)}$

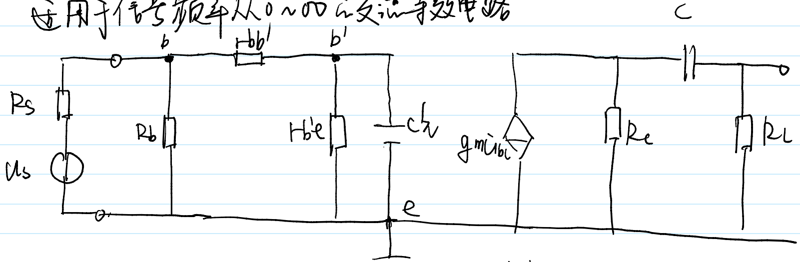
3) 波特图画法，决定

4) C_π的求法 f_β和C_{ob}可以查出（测得），$r_{b'e} = \frac{I_{EQ}}{U_T}(1+\beta_0)$，

$$C_\pi = \frac{1}{2\pi r_{b'e} f_\beta} - C_\mu$$

- 单管共射放大电路的三个频段

适用于信号频率从0~∞的交流等效电路



其中 $C'_\pi = C_\pi + C'_\mu$

$= C_\pi + C_\mu\cdot(1+g_m R'_L)$

$= C_{b'e} + C_{b'c}\cdot(1+g_m R'_L)$

输入段低通，输出端高通。

中频段，C'_π开路，C短路。
低频段，C'_π开路，考虑C。
高频段，考虑C'_π，c为短路

中频段，

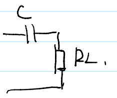
$$\dot{A}_{usm} = \frac{\dot{U}_o}{\dot{U}_s} = \frac{\dot{U}_i}{\dot{U}_s}\cdot\frac{\dot{U}_{b'e}}{\dot{U}_i}\cdot\frac{\dot{U}_o}{\dot{U}_{b'e}}$$

中：$\dot{A}_{usm} = \frac{R_i}{R_s+R_i}\cdot\frac{r_{b'e}}{r_{be}}\cdot\frac{-R_c/\!/R_L\cdot g_m\cdot r_{b'e}}{r_{b'e}} = \frac{R_i}{R_s+R_i}\cdot\frac{r_{b'e}}{r_{be}}\cdot g_m(R_c/\!/R_L) = \frac{R_i}{R_s+R_i}\cdot\frac{-\beta_0(R_c/\!/R_L)}{r_{be}}$

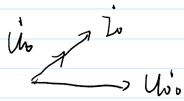
其中 $g_m = \frac{\beta_0}{r_{be}}$

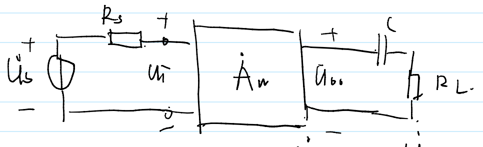
$$\dot{A}_{usm0} = \frac{R_i}{R_s+R_i}\cdot\frac{r_{b'e}}{r_{be}}\cdot(-g_m R_c) = \frac{R_i}{R_s+R_i}\cdot\frac{-\beta_0 R_c}{r_{be}}$$

低：



仅仅在负载处发生变化。





$$\dot{A}_{usl} = \frac{\dot{U}_o}{\dot{U}_s} = \frac{\dot{U}_{oo}}{\dot{U}_s}\cdot\frac{\dot{U}_o}{\dot{U}_{oo}} = \dot{A}_{usm0}\cdot\frac{R_L}{R_c + \frac{1}{j\omega C} + R_L}$$

输出电阻

$$= \dot{A}_{usm0}\cdot\frac{R_L}{(R_c+R_L)+\frac{1}{j\omega C}}\cdot\frac{R_c+R_L}{R_c+R_L}$$

$$= \dot{A}_{usm0}\cdot\frac{R_L}{1+j\omega C(R_c+R_L)}\cdot\frac{1}{R_c+R_L} = \dot{A}_{usm}\Big/ 1+\frac{1}{j\omega C\cdot(R_L+R_c)}$$

$\because 1 = 2\pi f_L\cdot C(R_L+R_c)$ $= \dot{A}_{usm}\cdot\frac{1}{1+\frac{f_L}{jf}} = \dot{A}_{usm}\cdot\frac{jf/f_L}{1+jf/f_L}$

频率响应分析。

$$\begin{cases} 20\lg|\dot{A}_{usl}| = 20\lg|\dot{A}_{usm}| - 20\lg\sqrt{1+(\frac{f_L}{f})^2} \\ \phi = \arctan\frac{f_L}{f} - 180^\circ \end{cases}$$

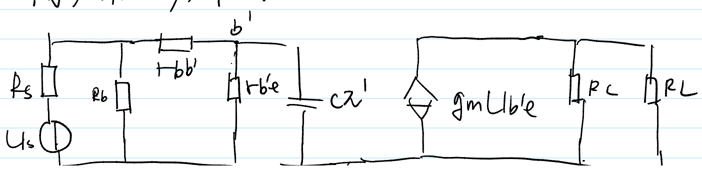
$f \gg f_L$，$20\lg|\dot{A}_{us}| \approx 20\lg|\dot{A}_{usm}|$

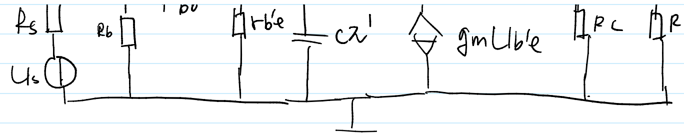
$f = f_L$，$20\lg|\dot{A}_{us}|$ 下降3dB，$\phi = -135^\circ$

$f \ll f_L$ $20\lg|\dot{A}_{us}\frac{f}{f_L}| \approx 20\lg|\dot{A}_{us}|$

$f \to 0$时 $|\dot{A}_{us}| \to 0$，$\phi = -90^\circ$

高频段的频率响应





这时 C_π' 不能忽略. C 因为 $\frac{1}{j\omega C}$ 较小, 可以忽略.

由于要和中频段做比较（回顾前面公式）

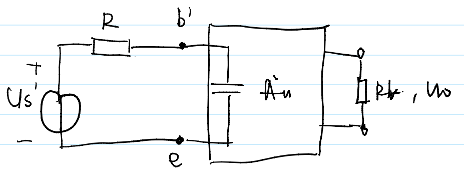
$$\dot A_{usm} = \frac{U_i}{U_s}\cdot\frac{U_{r'be}}{U_i}\cdot\frac{U_o}{U_{r'be}} = \frac{R_i}{R_s+R_i}\cdot\frac{r_{b'e}}{r_{be}}\cdot g_m R_c /\!/ R_L$$

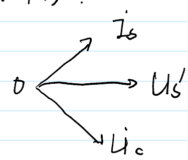
由于 $g_m r_{b'e} = \beta_0$　$g_m = \frac{\beta_0}{r_{b'e}}$，得.

$$\dot A_{usm} = \frac{U_i}{U_s}\cdot\frac{U_{r'be}}{U_i}\cdot\frac{U_o}{U_{r'be}} = \frac{R_i}{R_s+R_i}\cdot\frac{1}{r_{be}}\cdot\beta_0\cdot(R_c /\!/ R_L)$$

$$\dot A_{usm0} = \frac{R_i}{R_s+R_i}\cdot\frac{\beta_0 \cdot R_c}{r_{be}}$$

这时考虑 C_π' 的影响，对左右两侧进行戴维南等效.





这时 $\frac{\dot U_s'}{U_s} = \frac{\dot U_i}{\dot U_s}\cdot\frac{\dot U_{b'e}}{U_i} = \frac{R_i}{R_s+R_i}\cdot\frac{r_{b'e}}{r_{be}}$，$R = r_{be}' /\!/ [r_b + (R_s /\!/ R_b)]$

$$\dot A_{ush} = \frac{\dot U_o}{\dot U_s} = \frac{\dot U_s'}{\dot U_s}\cdot\frac{\dot U_{C\pi'}}{\dot U_s'}\cdot\frac{\dot U_o}{U_{C\pi'}} = \underline{\frac{R_i}{R_s+R_i}\cdot\frac{r_{b'e}}{r_{be}}}\cdot\underline{\frac{\frac{1}{j\omega C_\pi'}}{R+\frac{1}{j\omega C_\pi'}}}\cdot\underline{(-g_m R_L')}$$

$$= \dot A_{usm}\cdot\frac{\frac{1}{j\omega C_\pi'}}{R+\frac{1}{j\omega C_\pi'}} = \dot A_{usm}\frac{1}{j\omega C_\pi' R+1} = \dot A_{usm}\frac{1}{j\frac{f}{f_H}+1}$$

，注意低频是 $\frac{f_L}{jf}$，高频是 $\frac{jf}{f_H}$，在相位上的变化和表达式都有差别.

$$f_H = \frac{1}{2\pi\cdot R\cdot C} = \frac{1}{2\pi\cdot[r_{be}' /\!/ (r_b+(R_s/\!/R_b))]\,C_\pi'}$$

求频率响应就是求时间常数.

$$\begin{cases} 20\lg|\dot A_{ush}| = 20\lg|\dot A_{usm}| - 20\lg\left|1+\left(\frac{f}{f_H}\right)^2\right|^{\frac{1}{2}} \\ \varphi = -180^\circ - \arctan\frac{f}{f_H} \end{cases}$$

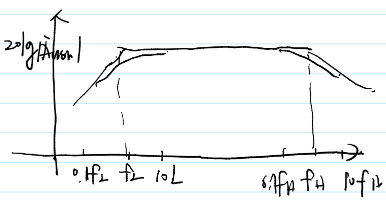
当 $f \ll f_H$ 时.
$20\lg|\dot A_{usm}| \approx 20\lg|\dot A_{usm}|$
$f = f_H$ 时.
$20\lg|\dot A_{usm}|$ 下降3dB，$\varphi = -225^\circ$，
$f \gg f_H$ 时.
$f \to 10$倍，下降20dB.
$f \to \infty$，相角约 270°.

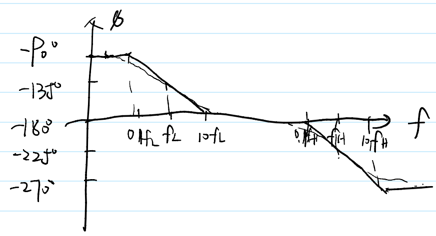
• 单管共射放大电路的波特图及带宽增益积.

全频段放大倍数表达式

$$\dot A_{us} = \frac{\dot U_o}{\dot U_s} = \frac{\dot A_{usm}}{\left(1+\frac{f_L}{jf}\right)\left(1+j\frac{f}{f_H}\right)}$$

波特图.





$$f_{bw} = f_H - f_L \approx f_H$$

$$f_{bw} = f_H - f_L \approx f_H$$

$$f_H = \frac{1}{2\pi C_\pi' [r_{b'e} // r_{bb'} + (R_s // R_b)]} \qquad C_\pi' = C_\pi + (1 + g_m R_L') C_\mu$$

$$C_\pi = \frac{1}{2\pi f_\beta r_{b'e}} - C_\mu$$

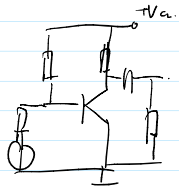
带宽增益积 $|\dot{A}_{usm} f_{bw}| \approx |\dot{A}_{usm} f_H|$

$$g_m R_L' \uparrow \rightarrow \begin{cases} C_\pi' \uparrow \rightarrow f_H \downarrow \\ \dot{A}_{usm} \uparrow \end{cases} \rightarrow$$

提高增益时，带宽变窄。
提高带宽时，增益将降低。

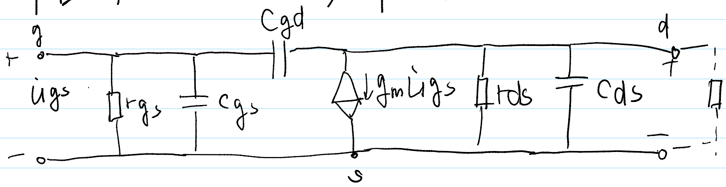
若 $r_{be} \ll R_b$，$R_s \ll R_b$　$g_m R_L' \gg 1$.　$g_m R_L' C_\mu \gg C_\pi$.　常规电路

R_b 为大电阻.



$$|\dot{A}_{usm}| = \frac{1}{2\pi (r_{bb'} + R_s) C_\mu}$$

• 单管共源放大电路的频率响应



C_{gd} 即影响输入回路，又影响输出回路，同 C_μ 效果相同。

$$I_{cgd} = \frac{U_{gs} - U_{ds}}{X_{cgd}} \qquad 设 \frac{U_{gs}}{U_{ds}} = k$$

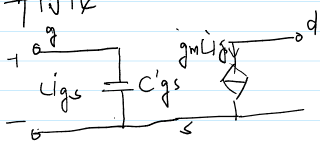
$$C_{gs}' = C_{gs} + (1 - \dot{k}) C_{gd} \qquad \dot{k} \approx -g_m R_L$$

$$C_{ds}' = C_{ds} + \frac{\dot{k} - 1}{\dot{k}} C_{gd}$$

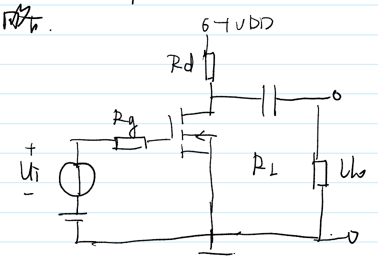
	R_{ds}/Ω	R_{gs}/Ω	C_{gs}/pF	C_{gd}/pF	C_{ds}/pF
结型	10^5	$>10^7$	$1\sim10$	$1\sim10$	$0.1\sim1$
绝缘栅型	10^4	$>10^9$	$1\sim10$	$1\sim10$	$0.1\sim1$

R_{ds}，R_{gs} 比外接电阻大得多，可以视为开路。
C_{ds}' 和 R_L' 较小，可忽略。

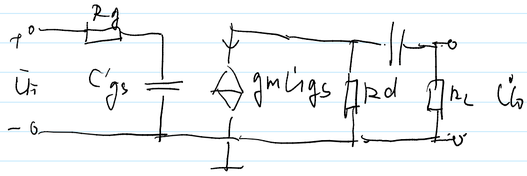
简化



简化模型.



单管共源放大电路



$$\dot{A}_{um} = \frac{U_o}{U_i} = -g_m R_L'$$

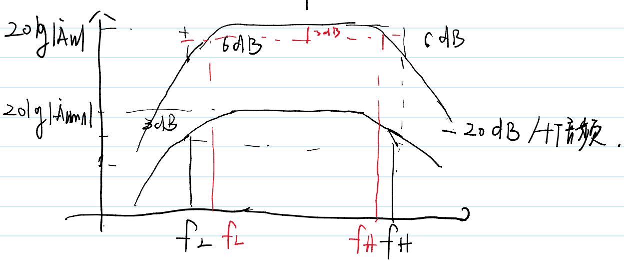
$$f_L = \frac{1}{2\pi (R_d + R_L) C} \qquad \left(\frac{R_c + R_L}{R_c + R_L}\right) 在三极管中，同时乘以了 \frac{R_c + R_L}{R_c + R_L}$$

$$f_H = \frac{1}{2\pi R_g C_{gs}'} \qquad 找到时间常数$$

$$\dot{A}_u = \dot{A}_{um} \cdot \frac{1}{(1 - j\frac{f_L}{f})(1 + j\frac{f}{f_H})}$$

$$\dot{A}_u = \dot{A}_{um} \cdot \frac{1}{(1-\frac{f_L}{jf})(1+\frac{jf}{f_H})}$$

• 多级放大电路的频率响应



$20\lg|\dot{A}_u| = 20\lg|\dot{A}_{u1}| + 20\lg|\dot{A}_{u2}| = 40\lg|\dot{A}_{u1}|$

$f_{H2} = 0.643 f_{H1}$，利用增益带宽积理解

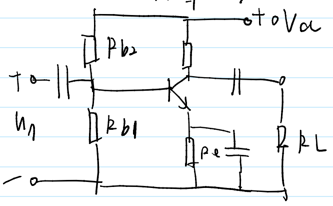
$f_{L1} \sim f_{Ln}$，$f_{H1} \sim f_{Hn}$.

$$\begin{cases} f_L > f_{Lk} \\ f_H < f_{Hk} \\ f_{bw} < f_{bw\,k} \end{cases} \qquad \begin{cases} 20\lg|\dot{A}_u| = \sum_{k=1}^{n} 20\lg|\dot{A}_{uk}| \\ \varphi = \sum_{k=1}^{n} \varphi_k \end{cases}$$

$f_L \approx 1.1\sqrt{\sum_{k=1}^{n} f_{Lk}^2}$ $\qquad \frac{1}{f_H} = 1.1\sqrt{\sum_{k=1}^{n} \left(\frac{1}{f_{Hk}}\right)^2}$，1.1为修正系数.

若某一级的下限频率远远高于其他级，可以认为这一级的f_L就是总体的f_L.

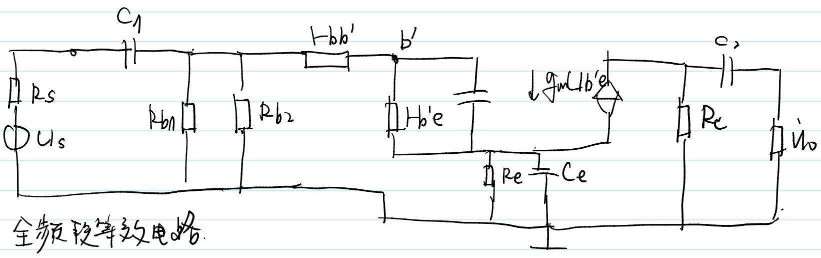
若某一级的上限截止频率远远低于其他级，可以认为这一级的f_H就是总体的f_H



1. 有多少个电容影响频率响应，放大倍数就有多少个因子

C_1, C_2, C_π', C_e

2.



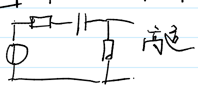
全频段等效电路

困难点在于，寻找回路的等效电阻.

考虑C_1（忽略其他电容，C_2，C_e短路，C_π'开路）

$\tau = [R_s + (R_{b1}//R_{b2}//r_{be})]C_1$.

考虑C_2（C_1，C_e短路，C_π开路） 物理意义相同



$\tau = (R_c + R_L)C_2$

考虑C_e，C_1，C_2短路，C_π'开路.

$\tau_e = (R_e // \frac{r_{be} + R_s//R_{b1}//R_{b2}}{1+\beta})$，电流流向处理.

考虑C_π'，C_1，C_2，C_e短路

$\tau_{c\pi} = [r_{b'e} // (r_{bb'} + R_s//R_{b1}//R_{b2})]C_\pi'$

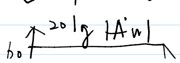
当$C_1 = C_2 = C_e$时，τ_e远小于τ_1, τ_2（C_e也相当于高通电路）

可以认为C_e决定下限频率. C_e容量应当较大.

$$\dot{A}_u = \dot{A}_{usm} \cdot \frac{1}{(1-\frac{f_{L1}}{jf})(1-\frac{f_{L2}}{jf})(1-\frac{f_{Le}}{jf})(1+\frac{jf}{f_H})}$$

• 频率响应的计算.

已知某放大电路的幅频特性曲线



1. 3级放大. 10f → 60dB.